REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
4 August 1998

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
MIT/ DRAPER TECHNOLOGY DEVELOPMENT PARTNERSHIP PROJECT: SYSTEMS ANALYSIS AND ON-STATION PROPULSION SUBSYSTEM DESIGN

5. FUNDING NUMBERS

6. AUTHOR(S)
Theodore E. Conklin

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technology

8. PERFORMING ORGANIZATION REPORT NUMBER
98-036

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
THE DEPARTMENT OF THE AIR FORCE
AFIT/CIA, BLDG 125
2950 P STREET
WPAFB OH 45433

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Unlimited distribution
In Accordance With AFI 35-205/AFIT Sup 1

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

19980810 091

14. SUBJECT TERMS

15. NUMBER OF PAGES
133

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

MIT / Draper Technology Development Partnership Project: Systems Analysis and On-Station Propulsion Subsystem Design

by
Theodore E. Conklin

B.S. Astronautical Engineering
United States Air Force Academy, 1996

Submitted to the Department of Aeronautics and Astronautics in partial fulfillment of the requirements for the degree of

Master of Engineering in Aeronautics and Astronautics

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1997

Author____

Department of Aeronautics and Astronautics
August 21, 1997

Certified by____

Charles Boppe
Senior Lecturer, Department of Aeronautics and Astronautics
Thesis Supervisor

Certified by____

John Deyst
Professor, Department of Aeronautics and Astronautics
Thesis Supervisor

Accepted by____

Jaime Peraire
Chairman, Departmental Graduate Committee

MIT / Draper Technology Development Partnership Project: Systems Analysis and On-Station Propulsion Subsystem Design

by
Theodore E. Conklin

Submitted to the Department of Aeronautics and Astronautics on 8 August, 1996,
in partial fulfillment of the requirements for the degree of Master of Engineering

Abstract

The objective of this thesis is to describe the process for, and the overall design that resulted from the MIT/Draper Project from August, 1996 to May, 1997, including the specific design of the on-station propulsion subsystem for the Wide Area Surveillance Projectile, WASP. A summary of the technological needs of this nation, as determined by the MIT/Draper Project team begins the thesis. Possible opportunity areas and project topics for the MIT/Draper team are identified, and market assessments for five different possible projects are discussed. Lessons learned during the first semester of project work are then discussed. An explanation of the reasons for selecting a sensor-equipped projectile is provided. A requirements analysis for WASP is performed based on the requirements established by the Draper Laboratory and possible customers for the product. Derived requirements are used to develop three possible WASP flyer concepts, from which one is selected. An analysis of the possible propulsion methods for WASP, resulting in the decision to further examine the two stroke engine option is explained, and the decision to keep the Wankel engine as a backup option in the design process is also discussed. Selection of the Super Shell design concept for WASP is explained, and a possible propulsion system is discussed, with a focus on the two-stroke engine. The remote starter system and propeller design are not discussed in detail due to project time constraints. Lastly, the future outlook for WASP and the on-station propulsion system are discussed.

Thesis Supervisor: Charles Boppe
Title: Senior Lecturer, Department of Aeronautics and Astronautics

Thesis Supervisor: John Deyst
Title: Professor of Aeronautics and Astronautics

Acknowledgments

I would like to thank everyone who helped me to make this thesis a reality. First, I would like to thank my family and friends for understanding that I could not spend all the time that I wanted with them during this project. Their understanding allowed me to contribute a significant amount of time to this project.

I would also like to thank the hard-working students and faculty of the MIT/Draper team. Without the other four MEng students, three UROP students, two SM students, and the project's faculty leadership through Charlie Boppe and John Deyst the project's success to date would not have been possible.

Table of Contents

List of Figures

List of Tables

Chapter 1 Introduction

1.1 MIT / Draper Partnership Project Concept and Objective

The MIT / Draper Technology Development Partnership Project is a two year project created in order to develop and demonstrate an innovative, first-of-a-kind system judged to be important to the needs of the nation [1]. Therefore, the purpose of this project is to look forward and outward in order to create a system that will help this nation move into the future. This type of project, and its initial six month research period in particular, were so different from the current method of choosing research projects that there was really no set way of doing things or recipe for the project to follow. However, though the method used in this project was new in many ways, the concept behind such a process was in no way revolutionary. In 1994, Gary Hamel and C.K. Prahalad of Harvard University published *Competing for the Future*, a book meant to help companies shape their own destiny through a process very similar to the one followed in the MIT / Draper Project [2].

Through substantial research, Hamel and Prahalad found that typically, "40% of senior executive time is spent looking outward, and of this time, about 30% is spent peering three, four, five, or more years into the future" [2]. Of this time spent looking into the future, "no more than 20% is spent attempting to build a collective view of the future" [2]. When these percentages are multiplied together, one finds that, on the average, senior management is devoting only 2.4% of its time building a corporate perspective on the future [2]. According to Hamel and Prahalad, it is this inward focus by senior management that has forced companies to make decisions day-by-day, or year-by-year, rather than with a vision for the future that will allow companies to move ahead of the competition for years to come. The MIT / Draper project was created with this theme in mind. Therefore, the background information, including the developing of a list of national needs, prioritizing the needs, and developing possible opportunity areas for the team, was an extremely important part of this project.

The process for this project, required that a substantial portion of the effort would be devoted to identifying the national needs, identifying the possible opportunity areas where this team could work effectively, and selecting the best project that answers multiple national needs. Six months of time was initially devoted to these areas. This initial research resulted in the publication of two documents. The first document, a Priorities and Opportunities Document, which was presented to the Draper Laboratory on 23 October, 1996, presented the national needs and team facility capability assessments that had been performed from August 1996 through October 1996 as well as the four opportunity areas of highest priority which the team derived based on the national needs and team capabilities [3].

After the publication of this document, the team began its market assessment of various possible concepts. This assessment continued through December of 1996, and the results were discussed in a presentation at the Draper Laboratory at the end of that month. At this presentation, the top five concepts were presented, and then the Draper Laboratory was asked to make a decision on which project the team would continue work. The Draper Laboratory selected what it titled the "Low-cost Instrumented Surveillance Projectile," or LISP, as the project that would be done. This project was later re-named the Wide Area Surveillance Projectile, or WASP. The design of WASP and specifically, the on-station propulsion system, is presented in Chapters 2 through 5 of this thesis.

The MIT / Draper Project was established as a two year project. Therefore, the initial group of Master of Engineering students worked on the project for the first year, which resulted in the preliminary design for the WASP. The second year of the project will involve the current Master of Science students, as well as a new team of Master of Engineering students. At the completion of the second year, the WASP is to be demonstrated in accordance with the requirements for the project that were established by the Draper Laboratory.

1.2 Background Work

A majority of the information used in Sections 1.2.1 through 1.2.4 of the thesis was adapted from the MIT / Draper student team's *Priorities & Opportunities Document* [3]. Information in this thesis differs from the material presented in the *Priorities & Opportunities Document* in that this thesis presents more of the research that the author conducted, rather than the entire team's research. This thesis also contains some of the author's feelings dealing with lessons to be learned from the way in which research was conducted during this portion of the project.

1.2.1 National Needs and Opportunities Assessment

The MIT / Draper Project started in August of 1996 with the identification of national technological needs, as well as the development of possible opportunity areas where the project team could be effective. This process began with the development of an organizational hierarchy showing how specific technologies would be determined for the team's investigation. This hierarchy is shown in Figure 1. For this project, a *need* was defined as "a useful thing that is required or desired to address some identified deficiency, which is the result of some given situation" [3]. A technology was then defined as "the means of applied science that society uses to provide its members with things that are required or desired" [3].

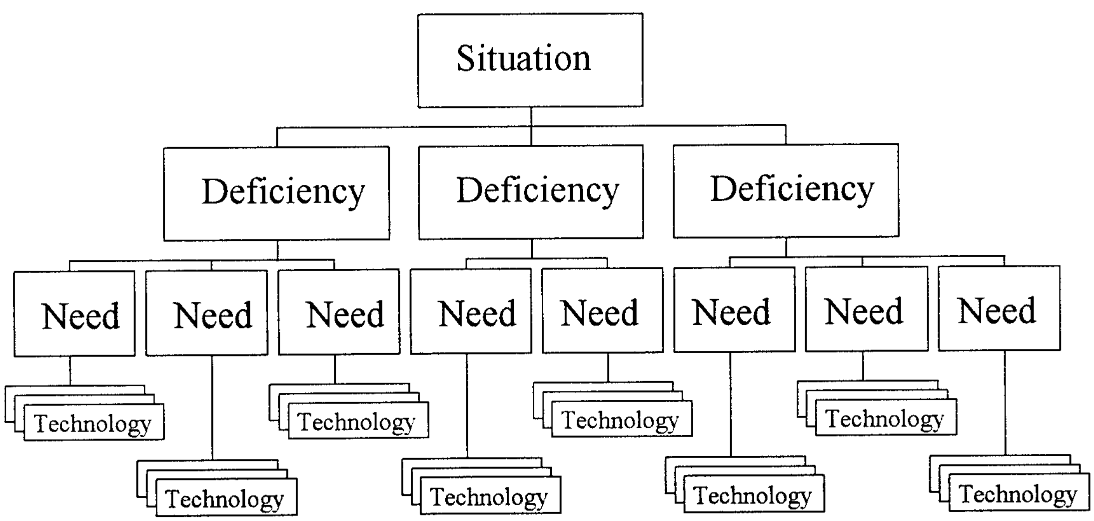


Figure 1: Hierarchy for Concept / Team Coordination

With this hierarchy in mind, the second step in this process was to establish a large enough library of information so that the team had a sufficient knowledge base in order to develop a list of

technical needs and priorities for the entire nation. The list of documents contained in this library can be found in Appendix A.

One of these documents, *The National Critical Technologies List*, published by the White House in March of 1995, became a significant part of the project [4]. This publication broke the nation's technological needs into seven main "Critical Needs Bins" where the nation must focus its research efforts in order to ensure United States national security and economic prosperity for the future. The seven needs bins were as follows:

1. Energy Efficiency & Independence
2. Environmental Quality
3. Information Access & Communication Effectiveness
4. Health Care & Agricultural Efficiency
5. Advanced Manufacturing
6. Improved Materials
7. Advanced Transportation

These seven general areas were used as a method of organizing the deficiencies and needs that the team pulled from publications in its library. A substantial database resulted from this analysis, which listed the specific field associated with each need bin. Major organizations that listed the specific field as a need for the future were also included in the database.

While this database was in development, the team performed an opportunities assessment using information from various publications in the library. The first step in the opportunities assessment process was to establish a list of criteria that the system must meet in order to satisfy the project's goals. Using the *MIT / Draper Technology Development Partnership Project* paper written during the summer of 1996, a list of six criteria was created [1]. The list read that the selected system should:

1. Be first-of-a-kind
2. Be an answer to a nationally important problem / opportunity / need
3. Be considered "high-risk," or possibly unobtainable
4. Be multi-disciplinary
5. Merge enabling technologies
6. Be marketable to multiple users

The result of this process was a list of many possible areas where the MIT/Draper Project could possibly be successful. The next step in this project was to then determine the specific capabilities of the entire team, including the Draper and Lincoln Laboratories. Once these capabilities were determined, the team was able to prioritize the opportunity areas and develop more well-refined concepts within the opportunity areas.

1.2.2 Facility Capability Assessment

This project was developed with the thought of using a number of MIT's academic departments, as well as the facilities at the Draper and Lincoln Laboratories, in order to produce the best system possible within the two-year time frame. Therefore, an evaluation of what facilities the team had available was a necessity. For this assessment, the team broke into three groups so that the Lincoln Laboratory, Draper Laboratory, and MIT could be investigated individually. Due to the fact that each element of the team is organized in a different way, the facility assessment was slightly different for each of the three team parts.

1.2.2.1 Charles Stark Draper Laboratory

The author of this thesis was tasked with determining and reporting the capabilities of the Draper Laboratory. For this assessment, the author investigated the current research projects at the Lab, as well as any projects that have started or been finished since 1992. Unfortunately, the author did not have access to any of the classified projects that Draper has managed or is currently managing. Therefore, the author made an assumption that by reviewing all of the unclassified projects from Draper Fiscal Year 1992 to present, the author would still be able to sufficiently evaluate the capabilities of the Lab, as well as the main focus of the research performed at Draper.

The author classified each of the projects from the Company Sponsored Research (CSR) and Individual Research & Development (IR&D) manuals from Draper Fiscal Year 1992 to present into one or more of the seven "Critical Needs Bins" listed earlier in this report. Many of the projects fit into more than one of the bins, so they were simply listed twice, rather than trying to force each project into only one specific bin. As one can see from Table 1, below, the main thrust

of Draper projects lies in two bins: Information Access & Communication Effectiveness and Advanced Transportation. However, there seemed to have been sufficient research at the Lab involving all seven "Critical Needs Bins" in the past four years such that the Draper Laboratory could be a significant help to the MIT / Draper Project no matter what particular bin the project happened to fall under. Specifically, Draper has seen a recent surge in the amount of research in the Advanced Manufacturing bin due the creation of the micro-mechanical division.

1.2.2.2 Lincoln Laboratory

For the assessment of Lincoln Laboratory capabilities, the *Lincoln Lab Journal*, published monthly, from 1991 to present was reviewed. Each of the articles in this journal summarized a particular research project at the Lincoln Lab, and therefore, each article was classified into one or more of the "Critical Needs Bins." Each Journal also listed the abstracts of additional projects at Lincoln as well as current Masters and Ph.D. theses. Similar to the Draper Lab, due to the large number of projects that have been worked on at the Draper Lab since 1991, only the projects determined to be most relevant to the MIT / Draper Project were accounted for.

As Table 1 shows, the work at the Lincoln Lab mainly deals with the Information Access & Communication Effectiveness "Critical Need Bin." Within this field, there seemed to be a thrust toward machine intelligence, adaptive optics, and advanced imaging. One other area where the Lincoln Lab has conducted significant research has been in the "Critical Need Bin" of Advanced Transportation, through their extensive work in the air traffic management field.

1.2.2.3 Massachusetts Institute of Technology

In order to determine the research focus of MIT, as well as the capabilities of the school of engineering, the current research projects of five departments were analyzed. The five departments were: Aeronautics and Astronautics, Mechanical Engineering, Material Science, Electrical Engineering / Computer Science, and Ocean Engineering. These five departments were each analyzed, rather than just the Department of Aeronautics and Astronautics because each of the departments listed may have done some research that would be beneficial to the MIT / Draper Project.

Aeronautics and Astronautics is currently involved in a broad range of research topics. Included in this list are: engine technologies, human factors issues, avionics, materials, and air traffic management. Therefore, most of the work in this department was classified under the Advanced Transportation "Critical Need Bin."

Mechanical Engineering also performs work in a large range of research fields. A significant amount of research is currently being conducted in the biomedical area, but there is also a large amount of research being performed in the area of robotics. This research has led to a strong interest in this department in the area of control of robots and unmanned systems. The research of the Mechanical Engineering Department can be summarized into three main "Critical Needs Bins": Information Access & Communication Effectiveness, Advanced Manufacturing, and Advanced Transportation.

Material Science may have the most focused research of any of the departments listed. A majority of the research in this department deals with the behavior of materials and trying to gain a better understanding of a specific material's behavior under different conditions. Research is also being conducted to investigate the role of particular materials in systems, such as through the corrosion of a material in an aircraft structure. Therefore, the research in the Department of Material Science can mostly be placed under the Improved Materials "Critical Need Bin."

At the time that this research was conducted, Electrical Engineering and Computer Science did not have a list of current research projects that the department was working on. Therefore, all information about its current status was obtained through discussions with various research groups. It was discovered through these groups that the range of projects is fairly broad, covering research from nano-fabrication to language, speech, and hearing studies. Human interface issues and parallel systems architecture are also being investigated. The majority of the projects in this department can be characterized as research in the Information Access & Communication Effectiveness "Critical Need Bin."

The research in the Department of Ocean Engineering has been fairly well-defined. The majority of the projects deal with the development of fluid dynamics simulations for ships, but research is also being conducted in the Unmanned Underwater Vehicle (UUV) area. Therefore, the work in this department can mostly be characterized as research in the Advanced Transportation "Critical Need Bin."

1.2.2.4 Facility Capabilities Summary

Table 1 summarizes facility capabilities. It shows the breakdown of the projects in each of the three main elements of the MIT / Draper Project Team that were researched for this project. The numbers shown in Table 1 represent the percentage of projects that were focused in each of the "Need Bins."

Table 1: Breakdown of MIT / Draper Team Projects Into Critical Needs Bins

Organizations and Elements	National Need Bin						
	1. Energy Efficiency & Independence	2. Environmental Quality	3. Information Access & Communication	4. Health Care & Agricultural Efficiency	5. Advanced Manufacturing	6. Improved Materials	7. Advanced Transportation
Draper Laboratory	6.5	3.2	35.5	4.9	11.3	4.9	33.9
Lincoln Laboratory	0.0	0.0	77.2	5.3	3.5	0.0	14.0
MIT Academic Departments							
Aero & Astro	2.9	5.0	21.6	11.7	0.7	13.6	44.5
EE & CS	12.9	8.1	54.8	16.1	8.1	0.0	0.0
Mat'l Sci. & Eng	7.5	5.0	10.0	7.5	2.5	57.5	10.0
Mech Eng	6.2	1.8	26.7	11.6	26.1	3.6	24.1
Ocean Eng	7.7	12.8	2.6	0.0	7.7	0.0	69.2

1.2.3 Opportunity Generation Process

Upon completion of the facilities capabilities research and the summarizing of the documents in Appendix A, the MIT / Draper team entered the opportunity generation phase of the project. During this phase, students and faculty met in large and small groups in order to brainstorm possible project topics. The facilities capabilities summary was used as a backbone to direct the

team in directions in which it could be successful. At the same time, information from the documents in Appendix A informed the team of national priorities, possible applications of new technologies, and undeveloped markets where the MIT / Draper Project could fill a current void. The figure below outlines the process followed by the team [3].

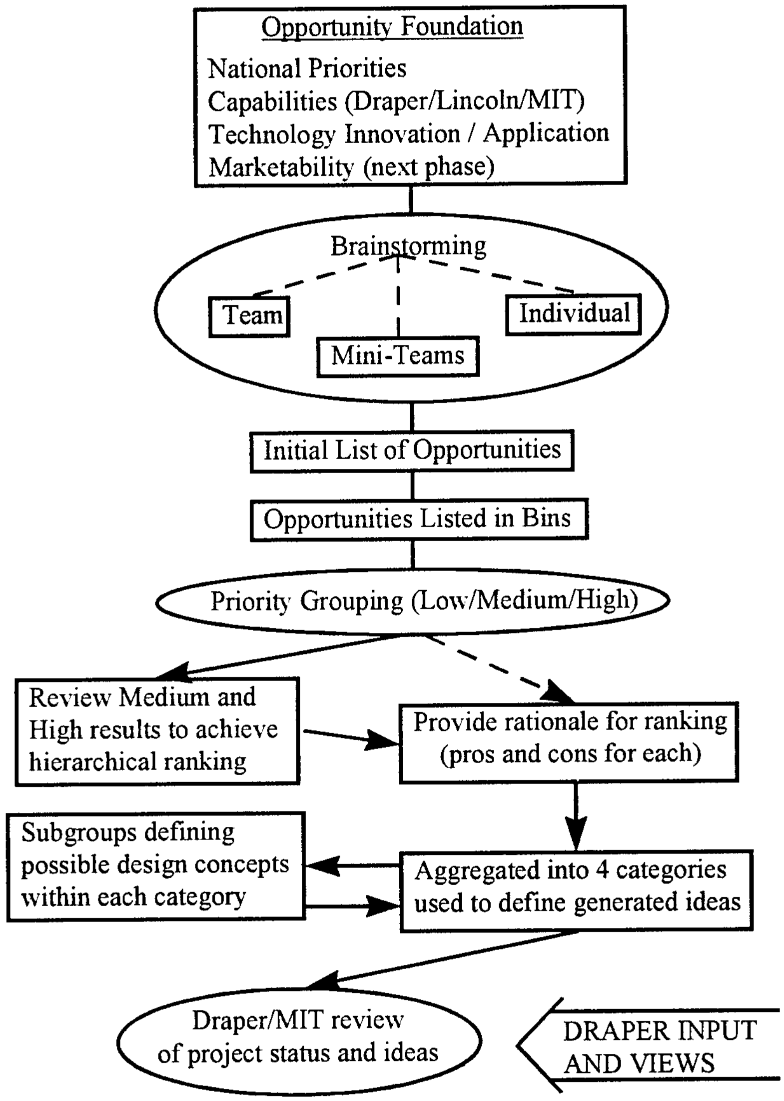


Figure 2: Opportunity Generation Process

As the figure shows, brainstorming was performed in three different ways: as a single team, as a few mini-teams, and as an individual. Each brainstormed idea that resulted from these sessions was given a ranking of High, Medium-High, Medium, Medium-Low, or Low which defined the idea's potential for further development. The ideas to which the team gave a ranking of Medium to High were kept for further review, and those below a ranking of Medium were eliminated. The possible opportunities that existed after this ranking process are listed below.

High

- Detection of chemical or biological agents present in the environment
- Explosives detection and countermeasures
- Improved air traffic control (ATC)
- Automated package delivery
- Free flight for aircraft
- Satellite-based ATC

Medium-High

- Mass manufacturing of small satellites
- Micro-systems with extreme g-tolerances
- Intelligent transportation systems
- New applications of gun technology
- Amphibious engine
- Unmanned vehicles for surveillance
- Automatic mapping vehicles

Medium

- Smart systems to assist humans in dangerous situations
- Search and rescue operations
- Automated rapid response disaster relief
- Cooperative sea / air / space search and rescue
- Hazardous waste dumping detection
- Emissions control
- Advanced simulation to assist aircraft designers
- Intelligent systems for recreational vehicles
- Friend / Foe identification systems and hardware

Once the ranking of these concepts was accomplished, it was noted that some brainstormed ideas were broad ideas, whereas others were well-defined, specific concepts. Rather than selecting among the brainstormed ideas at this point, the team chose to create four "opportunity areas," under which each of the remaining brainstormed ideas could be placed. The four opportunity areas that resulted from the grouping of brainstormed ideas were:

- Innovative Projectile Systems
- Intelligent Cooperative Systems
- Advanced Aircraft Navigation and Control
- Inexpensive Space Capability

The team then analyzed each of the four opportunity areas individually in order to determine the pros and cons of each area as a whole. After determining the pros and cons of each opportunity

area, the team planned to examine specific concepts within the areas that the team deemed worthy of further investigation. This process of generating many concepts and then downsizing the possible choices with the intention of expanding the list again at a later time is very similar to Pugh's "Divergent-Convergent Development Process" described in *Total Design* [5]. "Divergent-Convergent Development" is shown in the following figure:

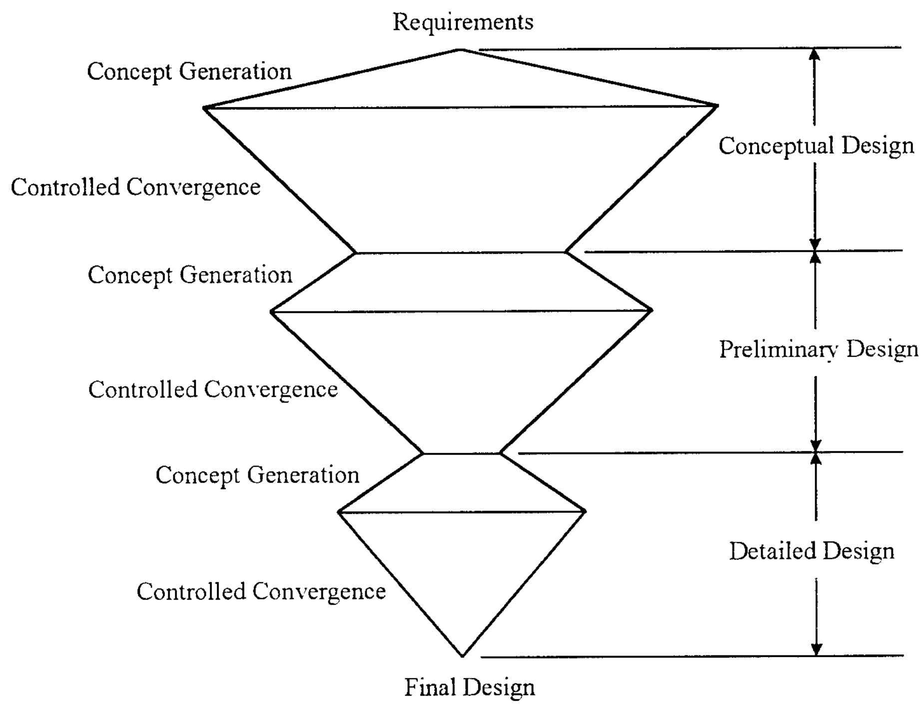


Figure 3: Divergent-Convergent Development

The Divergent-Convergent Development Process was intended to be applied to a project once a topic and its requirements have been established. However, this process was utilized throughout the MIT / Draper Project without actually having a defined project to work on. Rather, the requirements for the MIT / Draper Project were to determine a new, forward-looking project that could be completed in a two-year time period in response to a national technological need. Figure 3 states that the first phase of any project is the Conceptual Design Phase. For the MIT / Draper Project, the first phase was the opportunity generation process discussed above. This process started out with the generation of many possible concepts on which the team could possibly choose to work. When it was noticed that the brainstormed ideas were of vastly different sizes,

the team performed a "controlled convergence" of the concepts by creating four different opportunity areas under which the brainstormed ideas were placed.

Similarities between the team's process and Divergent-Convergent Development did not stop at this point. As will be discussed in later sections, once the four opportunity areas were developed, specific concepts within each area were examined, and a controlled convergence took place once again as certain concepts within each opportunity area were eliminated from contention. Remaining concepts were then examined in great detail, which included some preliminary design calculations, concept drawings, and market assessments. Finally, a controlled convergence occurred one last time which led to the final decision to pursue a particular project. Figure 3 displays this point as the "Final Design."

1.2.4 Opportunity Areas Assessments

Once the four opportunity areas were developed, the team met several times in order to determine the pros and cons of each area. Innovative Projectile Systems included all concepts that applied gun impulse technology to new applications in order to meet national needs. For example, it was envisioned that a sensor-equipped projectile could be launched over a forest fire area to give wind and fire intensity readings. A sensor-equipped projectile might also be launched by the Army or Navy in order to acquire images of a specific area. The pros and cons that the team determined for this opportunity area are listed below [3].

Table 2: Innovative Projectile Systems Pros and Cons

Pros	Cons
• Addresses: National defense Energy efficiency and independence Information access and communication effectiveness • Military and commercial applications • Potential low-cost alternative to UAVs • System's character fits capabilities	• Harsh environment • Small size constraints

The Intelligent Cooperative Systems area included any technology where smart systems can assist humans. For example, explosives detection performed by smart robots or aircraft, or unmanned

aircraft for surveillance were a couple of concepts in this area. The pros and cons for this area are listed below [3].

Table 3: Intelligent Cooperative Systems Pros and Cons

Pros	Cons
• Addresses: National defense Information access and communication effectiveness • Military and commercial applications • Possible advanced transportation system • System's character fits capabilities	• Scale of some projects may exceed project's resources • Potential for large amount of competition • Duplication of concepts possible

The Inexpensive Launch Capability area included any concepts that addressed the need for a more inexpensive method of sending satellites to orbit than those that currently exist. For example, a hybrid launch system that utilized the altitude of a balloon to lower the propulsive requirements for a satellite launch vehicle was one of the concepts in this area. The pros and cons for this area are listed below [3].

Table 4: Inexpensive Launch Capability Pros and Cons

Pros	Cons
• Addresses: National defense Information access and communication effectiveness Energy efficiency Advanced transportation Advanced manufacturing • Military and commercial applications • Large market developing for multiple-satellite constellations • Will have a high demand if costs can be significantly reduced • Much potential for innovation	• Competition from large companies (Hughes, TRW, Boeing) • Scale of some projects may exceed project's constraints

The Advanced Aircraft Navigation area included any concept that dealt with the increasingly crowding skies and an inadequate, outdated air traffic control system that this nation currently

uses. For example, a space-based ATC system that uses a network of satellites was envisioned for this opportunity area. The pros and cons that the team determined for this area are listed below [3].

Table 5: Advanced Aircraft Navigation Pros and Cons

Pros	Cons
• Addresses: National defense Information access and communication effectiveness Advanced transportation • Military and commercial applications • System's character fits capabilities	• Many organizations are already working ATC-related problems • Scale of some projects may exceed project's constraints • Potential marketing problem with government organizations, such as the FAA

1.2.5 Opportunity Area Concept Down-Selection

During the next phase of the MIT / Draper Project, specific concepts within each opportunity area were investigated in greater depth. After vigorous research of many concepts in each opportunity area, the team was able to consolidate the list of possible projects to one or two projects for each of the opportunity areas. Also, after discussions with air traffic controllers, as well as members of the MIT faculty and the Lincoln Laboratory, it was determined that the air traffic control problem that currently exists is flooded with research. This discovery led to the Advanced Aircraft Navigation opportunity area being eliminated for two basic reasons. First, the MIT/Draper team simply did not have the necessary background to compete in this field. It would have taken a significant amount of time to get up to speed in this area, which would not have made the two-year goal of the MIT/Draper Project feasible. Second, the scale of the air traffic control problem is larger than one that a team of ten students and two faculty members could handle. Some companies are currently devoting almost their entire list of resources to this issue, and therefore, it was not reasonable to assume that the MIT/Draper team could effectively compete in this market.

After the Advanced Aircraft Navigation opportunity area was eliminated, specific concepts within each of the remaining opportunity areas were researched. After many brainstorming sessions, web searches, patent searches, discussions with possible customers, and some preliminary calculations, the team was able to consolidate the list of possible projects to five. Teams of two

people then each continued work on one of the remaining concepts. In the area of Intelligent Cooperative Systems, the Autonomous Search and Rescue System (ASARS) and the Tailsitter Autonomous VTOL Vehicle both remained.

ASARS was a complete autonomous system that included aircraft, and both non-submersible and submersible vessels. Together, the sea and land-based system was planned to provide rapid surveillance and rescue response to a large-area where humans, alone, could not be successful. ASARS was designed to be used for catastrophic events such as plane crashes or boating accidents. This project required the use of Draper's knowledge in the areas of autonomous helicopters and submarines, and it would have required an enormous integration effort on the part of the MIT team.

The Tailsitter Autonomous VTOL Vehicle was planned to be an aircraft with high-speed cruise capability and multi-mission flexibility. It's characteristics were efficient cruise and hover, autonomous and cooperative operation, easily transportable on land or at sea, modular mission payloads, and a small footprint. Tailsitter could be used to replace humans in dangerous situations, such as land or sea search and rescue. It could also be used for reconnaissance and communications, as well as inexpensive cargo transportation in dangerous areas.

In the area of Inexpensive Space Capability, which was changed from Inexpensive Launch Capability, the Solar Sail to the Moon and the Hybrid Launch System remained. The Solar Sail concept was a project designed to prove the concept of using a sail for space propulsion and flight path control. The demonstrator to be designed by the team was intended to be a small satellite, propelled by a solar sail, that would travel to the moon. It was believed that the satellite would weigh approximately 80 kg, and it would take 120 days to reach the moon with a 70 square meter sail.

Matt Burba and the author worked together to define the Hybrid Launch System. This system was created to answer the problem of expensive space launch. A high-altitude balloon would take a launch vehicle and platform to an altitude of 100,000 feet, from where the launch vehicle would

launch. By increasing the launch point to this altitude, the amount of structure needed for the rocket is significantly reduced because the altitude gained by the balloon is significant, and the remaining dynamic pressure from 100,000 feet of altitude to space is much less than that experienced in the first 100,000 of altitude above the earth's surface. By decreasing the necessary support structure, a larger payload could be carried by a given rocket engine. It was planned that the rocket would use liquid oxygen and kerosene engines, much like those used on the Saturn V because this technology has been proven for many years, and it remains one of the most inexpensive propulsion methods for this reason. By using proven technology and increasing the payload mass fraction for the launch vehicle, it was believed that this system could significantly reduce launch costs.

A sensor-equipped projectile was the fifth concept that the team considered. This system had many possible applications. It could conduct airborne surveillance in the form of reconnaissance, targeting, or mapping. Projectiles may also be used as sensor arrays as many of them could be launched into a desired area, and they could return information about forest fires or hazardous materials. Therefore, the system had both military and civilian applications which gave this concept a large market potential.

1.2.6 Market Assessments of Five Concepts

Market assessments for each of the five concepts listed above were performed by the team. This thesis presents the market assessment results for the Hybrid Launch System. For market assessment results of the remaining four concepts, the *Market Assessment Document* should be referenced [6].

A schematic of the Hybrid Launch System is shown in Figure 4.

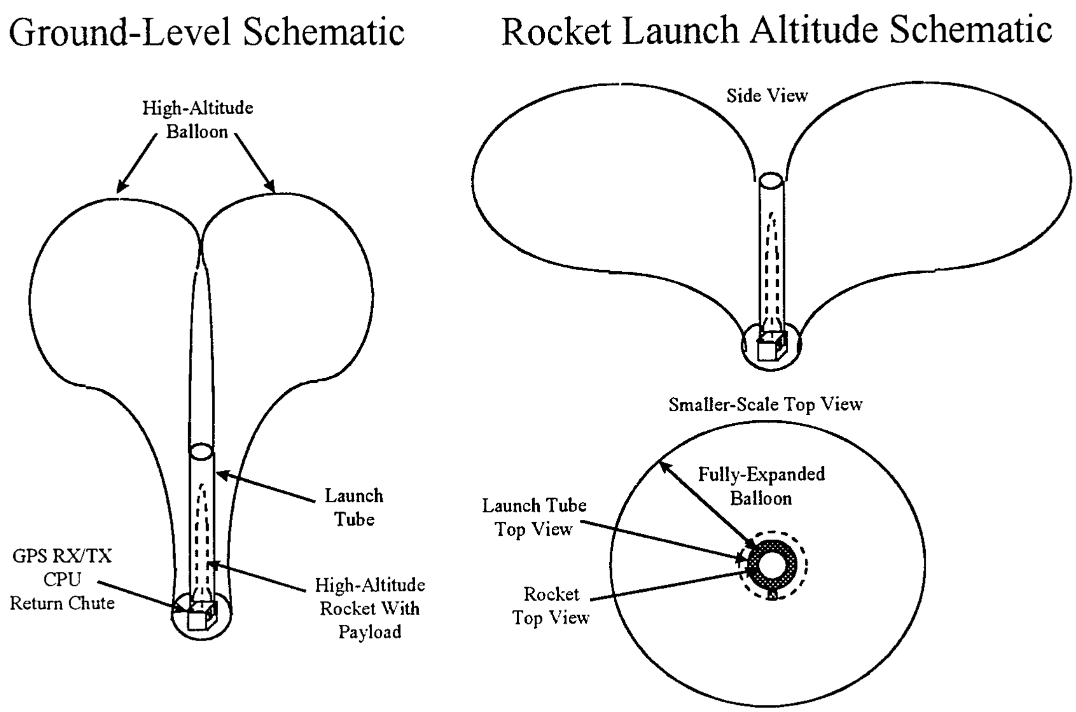


Figure 4: Hybrid Launch System

As shown in the diagram, the high-altitude balloon has a doughnut-like shape, which when at ground level does not leave a sufficient opening for the launch of the rocket. However, as the balloon increases in altitude, the helium gas inside expands, which creates an opening over the launch tube.

Web and patent searches were performed for this concept. The patent search only turned up concepts that would help with the design of the Hybrid Launch System, such as recently-designed high-altitude balloons by NASA. The web search, on the other hand, turned up an organization that was working on this concept. Called the High Altitude Lift-Off, or HALO, this organization was a team of approximately 60 part-time engineers who attempted to bring sounding rockets to 100,000 feet of altitude on a balloon before launching the rocket into sub-orbital altitudes. The purpose of the program was to prove how inexpensive this type of space launch could be by becoming the first amateur association to reach near-orbital altitudes.

A discussion with HALO's program manager, Gregory Allison, revealed some interesting things about this concept. First, HALO has been in progress for approximately two years, and at this point, Mr. Allison stated that it appears that it may be difficult to make money with this concept. When the entire system is completed, its total costs are actually much higher than one might think. He also stated that the system is not as easy as simply putting a rocket on a balloon. The actual design is also much more complex than one might believe.

However, statements by Mr. Allison were not sufficiently convincing to discard this concept completely. It was learned that for small satellite constellations, composed of many satellites, launch reliability is not as great a factor as it is for large communications satellites and the like. Rather, if hundreds of satellites are being launched, then the system can afford a lower launch reliability if costs are significantly lowered. Therefore, the Hybrid Launch System may have a lower reliability because of the system's complexity, but if it lowers launch costs, than a decrease in reliability may be acceptable.

One of the goals for the Draper Project was that the project should have a great deal of "unobtainium." For the Hybrid Launch System, the "unobtainium" was large, indeed. The product would certainly be new, and the market for the system would also be new for the Draper Laboratory. Together, these two facts place the system in the most difficult part of the market for success.

Though the market assessments for the other four concepts are not discussed here, it should be noted that no market assessment found a reason to eliminate a concept. Rather, in every case, possible organizations that would be willing to help the MIT/Draper team were found. All such organizations would actually be complementary to whatever project was chosen, and therefore, it appeared that all of the projects identified in the study had reasonable chances for success.

1.2.7 Project Selection

After the market assessment for each concept was completed, the results were presented to the Draper Laboratory. Prior to this presentation, the team held a vote in secret ballot to determine which project it would like to work on for the remaining two years. In this vote, the Solar Sail

was the team's first choice. For the second choice, three of the concepts actually scored approximately the same. The Hybrid Launch System, Sensor-Equipped Projectile, and Tailsitter all had approximately the same team interest. ASARS was decided to be the last choice. The results of this vote were presented to the Draper Laboratory in this manner, but due to the optimistic outlook for each concept based on the results of the market assessments, it was pointed out that the team would be happy to work on any of the five projects. Draper Laboratory held a closed session to make the decision on which project the team would continue work, and their decision was for the team to look at both the Sensor-Equipped Projectile and the Tailsitter for reconnaissance situations.

The team then decided that ten students was realistically only enough man-power for one project, and therefore, the Sensor-Equipped Projectile was chosen to be the MIT/Draper Project. At this point, the first semester of research stopped. During the break between semesters, the Draper Laboratory and members of the MIT faculty met in order to determine the system requirements for the Sensor-Equipped Projectile. This document was published in early January, 1997, and the requirements analysis began at this point. Chapter 2 is a complete discussion of the requirements analysis and resulting functional flows and top-level system architecture.

Chapter 2 Requirements Analysis and Top-Level System Architecture

2.1 System Requirements

Prior to the students' return from Christmas Break in early 1997, the Draper Lab and MIT faculty produced a document titled *Low-cost Instrumented Surveillance Projectile (LISP) System Requirements*, which stated the system requirements for the project [7]. The system described in these requirements was titled the Low-cost Instrumented Surveillance Projectile, LISP. Since the publication of Reference 7, the MIT / Draper Project has been re-titled the Wide Area Surveillance Projectile, WASP, which is how the system will be referred to throughout the rest of this thesis. These initial requirements for WASP from Reference 7 were used to create the first set of customer requirements for the Quality Function Deployment matrix, or QFD matrix, which is discussed in Section 2.2 of this report. These requirements are listed below:

- Compatible with Army 155 mm and Navy 5 inch artillery shells
- 70-200 mile range
- 1-8 hour mission time with a 2 hour operational time
- Provide near real-time information
- Some degree of autonomous operation that is to be defined
- Self-destruct mechanism that limits the size of the remaining pieces to smaller than the size of a can of cat food (8 ounces)
- Each vehicle costs between $20,000 and $30,000

Once these requirements were established, the next step involved prioritizing them in order to determine the most and least important requirements for the design of WASP. For this prioritization, the team met several times and discussed each requirement in detail. Relative weightings from one to ten were assigned to each requirement. A ten denoted a significantly important requirement, or a requirement that is not very tradable with respect to the other requirements, and a weighting of one meant that the requirement was less significant, or more tradable in comparison to other requirements. By establishing a range of requirements from least to most important, or most to least tradable, the team would be able to determine what design aspects were most important for WASP. The following customer requirements and weightings table was the result of these team discussions.

Table 6: Customer Requirements and Weightings

Requirement	Weighting (1-10)
Long Loiter	10
Long Operational Time	10
Low Cost	10
Ease of Operations	10
Very Safe	10
Accurate Image Position Determination	9
Near Real-Time Information Processing	9
Ease of Maintainability	9
Max Field-of-View	8
Max Image Resolution	8
High Degree of Autonomy	8
High Reliability	8
Long Range	5
Strong Stealth Characteristics	5
High Extensibility	5
Minimal Self-Destruct Debris	4
Long Shelf Life	4
Short Launch Time	3

At this point, it would have been presumptuous for the team to proceed with the weightings listed in Table 6 without actually contacting some of the possible customers for WASP, such as the Army and Navy. Therefore, during a visit to Picatinny Arsenal in New Jersey on 26 February, 1997 by a sub-group of five of the MIT/Draper team, the weightings in Table 6 were discussed. Members of the Picatinny Arsenal stated that they agreed with the team's prioritization. The only change made was that safety was determined not to be tradable, rather it was more like a constraint. The team then proceeded to build a Quality Function Deployment matrix.

2.2 Quality Function Deployment (QFD) Build

Quality Function Deployment, also referred to as the "House of Quality," is a systematic way to organize requirements and attributes. The value of this type of analysis for any project is that it results in a graphical translation of customer requirements into the parameters or attributes of the product and its manufacturing and quality control processes [8]. This type of analysis becomes extremely important when Integrated Product Development teams are being used because it

prioritizes technical requirements, eliminates human biases, provides a communication mechanism, and provides requirements traceability [8].

The customer needs and their weightings from Table 6 are the first elements of the QFD to be entered into the matrix. This list is placed at the left-hand side of the matrix. The next step in the creation of the QFD is to determine the technical requirements for each of the customer needs. The technical requirements for the MIT/Draper Project were developed through several brainstorming sessions. Each customer need was analyzed individually by developing a list of all of the technical requirements that are needed in order to make the customer need a reality. A customer need may only have one technical requirement, or it may have several. Once each customer need was analyzed, a final list of technical requirements was compiled by eliminating any of the overlap in technical requirements between different customer needs. This final list of technical requirements was entered across the top of the table.

The next step in the development of the QFD matrix was to determine how well each of the technical requirements answered the customer needs. The entire list of customer needs was reviewed for each of the derived technical requirements in order to determine how well each technical requirement satisfies each customer need. If a technical requirement worked directly to satisfy a customer need, then a 9 was placed in the box corresponding to both the technical and customer need. If a technical requirement helped satisfy a customer need, but it was not necessarily the most important technical requirement, then a 6 was placed in the box corresponding to both the technical requirement and customer need. Lastly, if a technical requirement satisfied a customer need in some small, indirect manner, then a 3 was placed in the box corresponding to both the technical and customer need. By multiplying the correlation numbers, 3, 6, or 9, by the weightings for the corresponding customer needs and summing the values, the absolute importance number for each technical requirement was created. The scores were then computed in a relative manner and placed on an importance scale of 1 to 10, with 10 being the highest importance. The computation of relative scores was performed because QFD's value is in showing the relative importance of technical requirements, not the absolute importance.

Lastly, the top, or roof, of the "House of Quality" was created. The purpose of the roof is to identify conflicts between technical requirements. It is a fact of almost every design that the requirement of one subsystem will conflict with the requirement of another subsystem. The creation of the roof helps to identify such conflicts at a very early time in the design process. For the WASP QFD requirements matrix, if a conflict between two technical requirements existed, then an open circle was placed in the box corresponding to both technical requirements. If a conflict existed between two technical requirements, each with absolute scores over 200, then a solid circle was placed in the box corresponding to both technical requirements to indicate a significant conflict. The WASP QFD, shown in Appendix C, displays the 51 technical requirements that the team derived from the 18 customer needs. The technical requirements that resulted in total scores of over 200 from the MIT/Draper team's analysis are listed below:

Table 7: Technical Requirements With Scores Over 200 for WASP

Technical Requirement	Total Technical Importance	Relative Importance
Flight System Disturbance Rejection	265	10
Lightweight Materials	265	10
Large Bandwidth Communication	246	10
Robust Power System	245	10
Robust Shell	237	9
Efficient On-Station Propulsion	236	9
Flight Sensor System	228	9
Low Subsystem Power Requirement	227	9
High Energy Density	224	9
High Data Throughput	220	9
Low Inert Mass Fraction	218	9
On-board Intelligence	202	8
Maximize Automated Functions	201	8

These high-ranking requirements gave the team insight into where a large majority of the design effort should be focused. Several of the requirements that were listed in Table 7 surprised the team, which is a typical result of developing a QFD matrix. Recall, QFD helps to remove human biases from the design process. In any project, some of the requirements thought to be the most important may not be listed as the most important by the QFD matrix. This type of result certainly should not be overlooked or ignored because it is this type of result that is desired by

anyone performing a QFD analysis. The QFD matrix objectively determines where design efforts should be focused. Therefore, if the results of a particular QFD matrix show significant deviation from the expected results, a sanity check should be performed to determine whether or not the correct correlation numbers were assigned for various technical and customer requirements. However, this does not mean that the QFD matrix should be adjusted to match the team's expected results. It is possible to manipulate any QFD matrix to give the desired results, but doing so simply negates a major reason for performing the QFD analysis. Rather, once the sanity check is completed, and if deviations from the expected results still exist, then the project team needs to ask the question, "Is this technical requirement more important than we thought?" The answer may be yes in some cases, and therefore, more effort may need to be devoted to a particular area of the design than was originally estimated. In this manner, QFD is extremely valuable to a project's development in this.

Another important result of QFD analysis is that the QFD matrix is almost never in a final form. The development of a QFD matrix is an iterative process, and as many team members as possible should be present when changes are made. The differences in personality and backgrounds of each person contribute to the development of the QFD matrix in many ways. For the MIT/Draper Project, one mistake made in first developing the QFD matrix was that its development was assigned to two individuals. When the results of this first QFD matrix were presented, it was found that many of the other team members disagreed with the results. The entire QFD matrix was then revamped to better include all team members' inputs, which resulted in the development of the initial QFD matrix requiring significantly more time than was necessary. Therefore, for future projects, when a QFD analysis is performed, as many people as possible of varying personalities and backgrounds should be included so that the QFD matrix is a representation of many members' thoughts, rather than a small sub-group. Putting this amount of time into the QFD matrix early in the process eliminates the time required for disagreements between the team at a later time.

It was important to the success of the WASP Project to discuss the customer requirements not only with members of the Draper Laboratory, but also with the likely final customers of the

WASP system: the Army and Navy. Some changes in the requirements were made based on these discussions with the Lincoln Laboratory, Picatinny Arsenal, and Dahlgren, the US Navy's test facility. The refined requirements reflect the system's desired market niche of being a quick-response surveillance vehicle:

- Flyer range was defined as the distance from launch to the desired surveillance area, or approximately 20 kilometers. The flyer would not have to cruise a significant distance beyond this point.
- Loiter time requirement goal was set at 1 hour, but 20 to 30 minutes was the minimum.
- Operational time was set equal to the loiter time.
- The image resolution was set to 1 meter, which will later be shown to drive the propulsion requirements.
- An image should be sent to the ground station at least once every few minutes. It was found that more than once every 9 seconds would be an information overflow.
- The desired cost per vehicle was reduced to $2,000 to $3,000 per vehicle, but this requirement was accepted as very tradable. Therefore, a maximum cost per vehicle was set at the original requirement of $20,000 to $30,000 per vehicle.

All of the analyses presented from this point on reflect these refined requirements, as well as the unchanged original requirements. When the term "requirement" is used, it is referring to an unchanged original requirement or one of the refined requirements.

2.3 Mission Scenarios

A statement of purpose for the WASP system was established based on the analysis performed in Sections 2.1 and 2.2:

> The system's goal is to provide military commanders with a rapid reconnaissance capability through the development of a projectile equipped with surveillance sensors and launched from 155 mm or 5 inch guns.

Various possible mission scenarios were derived from this statement, and Table 8 was developed to compare them. The magnitude of the requirements for each scenario increases as one reads down the table. For example, the long endurance mission at the bottom of the table has a greater range requirement than the damage assessment scenario toward the top of the table. Table 8 was adapted from Bernstein [9].

Table 8: Mission Scenarios Comparison

Mission	Range	Loiter	Oper. Time	Resp. Time	Surv. Area	Customer Cost Limits
Company Recon	~75 km	<30 min	<30 min	minutes	1-2 sq. km	$10,000
Damage Assessment	75+ km	<30 min	<30 min	minutes - hours	1-10 sq. km	$20,000-$30,000
Signals Intel	75+ km	>4 hrs	>4 hrs	hours	1-10 sq.km	$20,000-$30,000
Comm. Relay	75+ km	>4 hrs	>4 hrs	hours	1-10 sq.km	$20,000-$30,000
Route Recon	100+ km	N/A	=dist./speed	hours	= flight dist.	$20,000
Scud Hunting	150-200 km	<30 min	<30 min	hours	1-2 sq. km	$20,000
Hunter / Killer	100+ km	>4 hrs	>4 hrs	hours	1-10 sq. km	$20,000-$30,000
Area Surv.	75+ km	>4 hrs	>2 hrs	hours	>140 sq. km	$20,000-$30,000
Long Endurance	100+ km	>4 hrs	>4 hrs	hours	>140 sq. km	$30,000

Three general types of missions are shown above: long duration missions, information systems missions, and short duration missions. The long duration missions include large area surveillance (large viewable area), long endurance reconnaissance (long loiter), and route reconnaissance (fly a pre-programmed path). The information systems missions include signals intelligence (electromagnetic detection) and communications relay (allows for beyond line-of-sight communication). The short duration missions include company-level reconnaissance (fast response with short operational time and range), damage assessment (image sensor determines battle damage), "Scud hunting" (fast response to locate mobile launchers), and hunter/killer (locate and attack targets).

2.4 Functional Flow Diagram (FFD) Build

The FFD was the next logical step in the design process after analyses of the system requirements and possible mission scenarios were performed. Based on these analyses, the FFD served to illustrate the chronology of the WASP system operations [10]. The structure of the FFD led to a system configuration for a possible mission scenario. The FFD breaks a system into its functions, and therefore, for each mission scenario, a different WASP FFD resulted. For the WASP system,

the FFD served to define its specific functions so that these functions could be grouped into subsystems, and the major elements of the system could be determined.

The following example was adapted from Hallam [11]. One of the FFD functions for the WASP system might read "fly pre-programmed mission path." Such a statement implies that the flyer will have some sort of on-board guidance and control system that operates at some level of autonomy. FFD's, in general, also help to break each function into smaller functions, or sub-elements, as shown in the figure below.

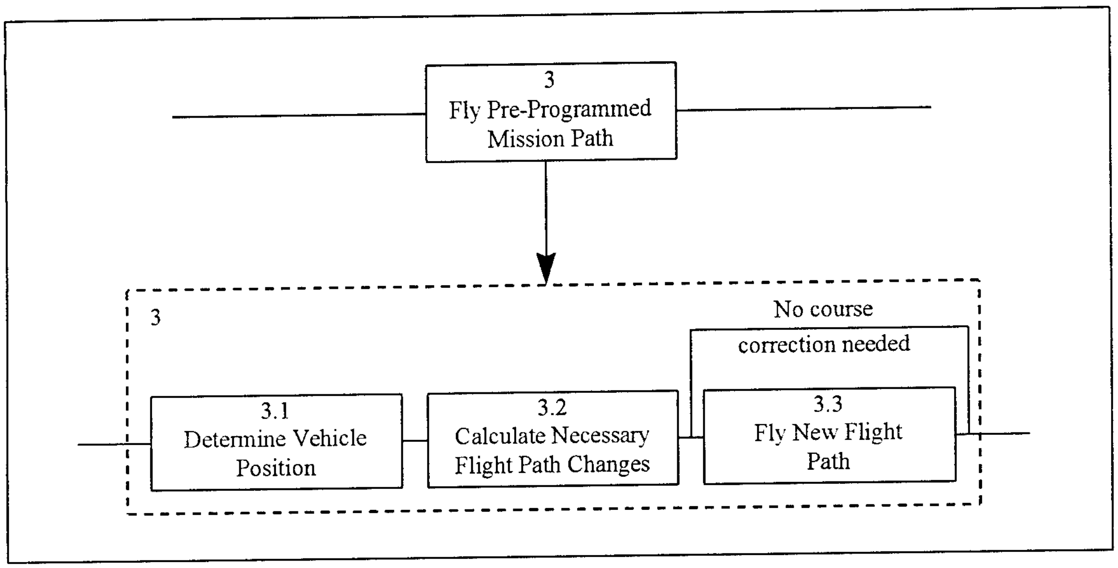


Figure 5: FFD Function Decomposition

The performance requirements for a given system can begin to be seen at this point in the design process. The text of the FFD actually implies that these performance requirements exist. For example, block 3.1 in the figure above, "Determine Position," implies that knowing the vehicle's position with some level of accuracy is important to the vehicle achieving its desired mission. When this block is analyzed by a design team, questions such as "How accurately must the vehicle know its position?" are asked. From this point, the team can move forward with defining how well the vehicle needs to perform some of its functions, and therefore, determine the performance requirements.

The FFD for the WASP system was developed by the team by placing small pieces of paper, each displaying one system function, on a wall so that the order of the functions could be easily rearranged. The team organized the functions were organized to create the first cut for the WASP system FFD. This first cut represented a baseline design for WASP, which was then altered to satisfy each of the missions listed in Table 8, but the baseline, itself, was not optimized. The first cut FFD is presented in Appendix B. Once the FFD's were developed, the system architecture could be derived, as the next section discusses.

2.5 Top-Level System Architecture

Once the FFD was developed, specific functions could be assigned to elements of the complete system. Based on these functions, the elements of the system were determined by deciding which functions could be combined into common system elements. The WASP top-level system architecture in Figure 6 resulted from this analysis.

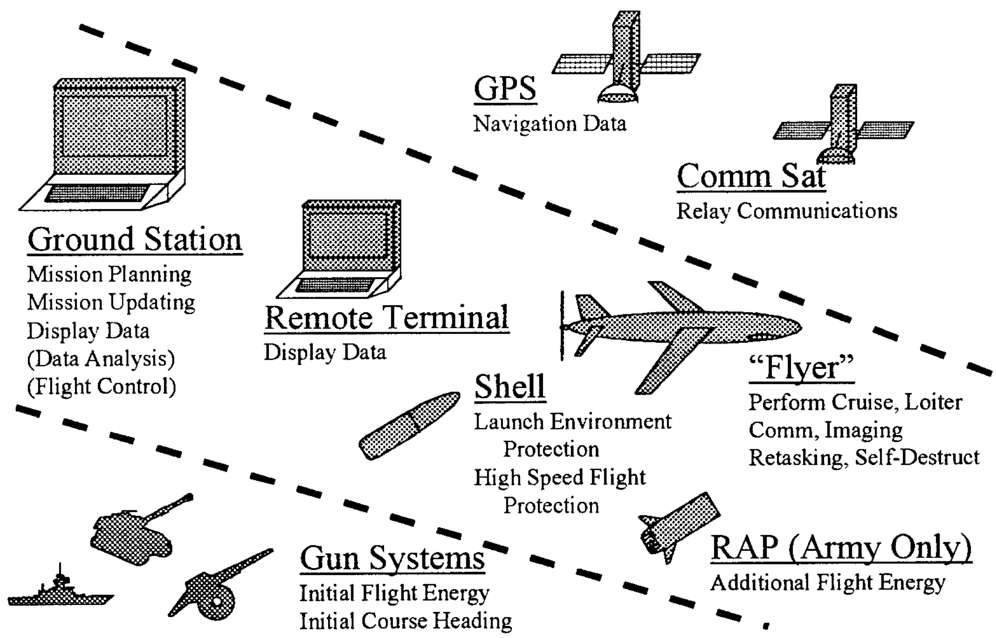


Figure 6: Top-Level System Architecture for WASP

The following descriptions of the WASP system elements were adapted from Bernstein [9]. The purpose of the ground station was to provide the interface between the WASP system hardware and the human user of the system. It was decided that the ground station would be used to pre-program WASP's mission. When WASP is launched, the ground station will be used to receive

images from the flyer for the duration of the mission. It is anticipated that the user could update WASP's mission at any point based on analyzing the down-linked data.

A remote terminal is included in the system in order to help put the reconnaissance information into the hands of the users. Therefore, the design includes a small, easy to carry unit that will display the WASP images to the user, but this remote terminal will not provide the unit with the ability to update WASP's mission.

The shell is defined as the element of the system that enables the interface to the gun. One of the major constraints for the WASP system is that it be compatible with the Navy's 5 inch or the Army's 155 mm guns. The g-forces experienced by current shells in these guns can range from 10,000 to 30,000 g's, which significantly complicates the design of WASP. Also, the Army and Navy guns are rifled so that the exiting shells spin at approximately 250 Hz. Therefore, WASP would have to be able to survive the high spin rate, or some other type of hardware interface would have to be used, such as a slip obturator, so that the entire WASP vehicle did not have to experience the high spin rate.

The flyer is defined as the vehicle element of the WASP system that would carry the sensor payload, loiter over and take images of a desired area, and relay the information to a ground station. Since one mission of the flyer is to gain reconnaissance information on an area, it had a requirement to remain stealthy, and therefore, it is planned to be equipped with a self-destruct mechanism that will fire when the mission is complete.

There were various other external elements that will be required in order to make the WASP system operational. The term external elements is intended to imply necessary parts of the WASP system that will not be modified by the WASP design team. Two important external elements of the WASP system are the 155 mm Army gun and the 5 inch Mk. 54 ship-mounted cannon, used for launching the WASP flyer. Also, in order for the WASP flyer to navigate it will require the use of the Global Positioning System, which is another external element. Similarly, if WASP is to communicate beyond line-of-sight, then it will require some type of communications link. Various

methods for performing this link are possible, such as communications satellites, the GPS network, and other UAVs.

The elements of the WASP system discussed above create the top-level architecture for the complete system. Using these elements to create a basic framework for the system that would be common to any design, conceptual designs for the WASP system could begin to be developed. At this point in the project, members of the MIT student team were assigned specific areas of the WASP design that they would be responsible for. The author was responsible for the development of the on-station propulsion system for the flyer.

Prior to developing flyer concepts, the author tried to get an idea of the requirements for the propulsion system, regardless of what the final design might be. Therefore, the capabilities of a possible vision sensor to be used on the WASP flyer were determined. During this period, various flyer concepts were being derived by the team, but propulsion subsystem designs were not further refined until the concepts were down-selected to three well-defined concepts. This thesis presents the chronology of the propulsion subsystem design. Chapter 3 discusses the sensor requirements and the quantitative propulsion requirements that resulted from the sensor analysis, and Chapter 4 discusses the comparison of various types of propulsion systems that were investigated. The analyses in both of these chapters were performed before the team narrowed its design option to three flyer concepts. The three flyer concepts, and the selection of one of the flyers for continued development, are presented in Chapter 5. Continuing chronologically, Chapter 6 then discusses the preliminary design for the chosen WASP flyer.

Chapter 3 On-Station Propulsion Requirements Calculations

3.1 Sensor Requirements Drive Propulsion Requirements

In a presentation given at MIT on 14 November, 1996 by Tom Coughlin of the Applied Physics Lab (APL) the reasons for success for the Near Earth Asteroid Rendezvous Spacecraft were discussed [12]. Coughlin stated that an early, clear definition of the NEAR satellite as a science mission meant that the design team would focus on using proven technologies in order to create a satellite that would produce useful information to scientists on earth.

A similar decision could be made about the WASP system. According to the refined requirements, one significant mission for WASP is toproduce images of a desired area forward of American troops with approximately one meter resolution. This requirement, combined with the short timeline allotted for this project, led to the team's looking to use "proven technologies," or "off-the-shelf" components, wherever possible.

Early in the design process, the team discovered the Xybion Electronic Systems Corporation's puck-sized imaging camera, which was being developed for high-g applications. The specifications for this product formed the baseline for the initial analysis done for the propulsion system requirements. Xybion stated that the camera had a CCD array of 500 pixels in height by 800 pixels in length and a focal length range of 6.3 mm to 100 mm [13]. By requiring a certain focal length for the camera, the team could use simple geometry to determine the maximum altitude where WASP could loiter and still meet the one meter resolution requirement. Unfortunately, the Xybion camera does not have a zoom capability, and therefore, for a given focal length, the resolution of the sensor will increase as the altitude of the flyer decreases. Without a zoom lens, a study must also be performed in order to determine the minimum size focal length, so as to require the least amount of weight and volume, that still meets the one meter resolution requirement.

The first step in determining the Xybion sensor's capabilities was to determine the sensor's field-of-view for the range of focal lengths using the following equation [14]:

$$\theta = 2\tan^{-1}\left(\frac{r_d}{f}\right) \tag{3.1}$$

where: r_d is half of the image plane length and f is the focal length. The resolution of a single pixel, in radians, could then be determined by dividing the field-of-view by the number of pixels in the CCD's height or width. The team chose to use 500 pixels for this calculation, the number of pixels in the array's height, because this number would give a larger value for the resolution than if the array's length were to be used. Therefore, by using the number of pixels in the array's height, the resolutions calculated would be more conservative than if the 800 pixels in the array's length were to be used.

$$Resolution/pixel = \frac{\theta}{500} \tag{3.2}$$

Lastly, the resolution, in radians per pixel, was multiplied by the sensor's altitude in order to determine the sensor's resolution in meters per pixel. The results of these calculations were then plotted on three different graphs. Figure 7 is a plot of how the field-of-view for the sensor decreases as the sensor's focal length increases.

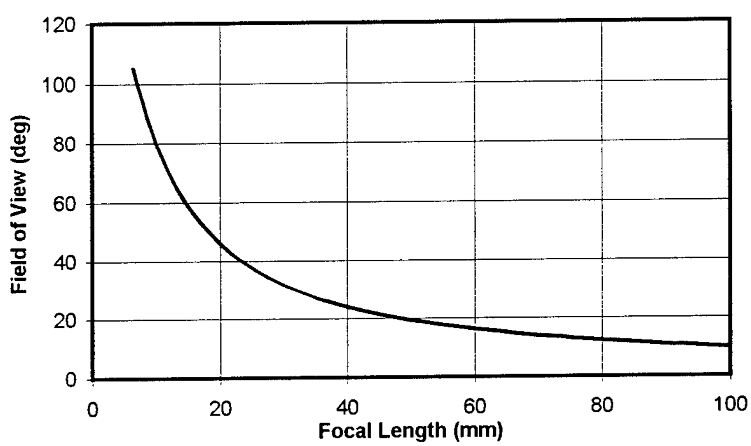


Figure 7: Sensor Field-of-View for Xybion-Specified Focal Lengths

The field-of-view decreases rapidly from 6.5 mm to 40 mm focal length, but from 40 mm to 100 mm, the field-of-view only decreases from approximately 20 degrees to 10 degrees. Obviously, the WASP flyer would like to see as much ground area as possible at one meter resolution for a

given altitude. Therefore, the valuable information that this plot provides is that it aids in the calculation of the coverage area at a focal length.

Figure 8 is a plot of how the sensor's resolution for given altitudes decreases as the focal length increases.

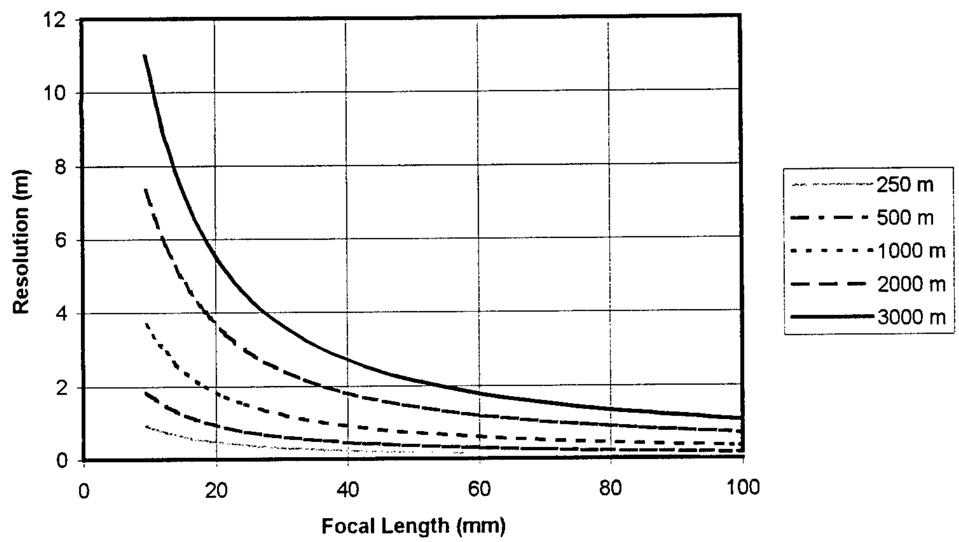


Figure 8: Xybion Sensor Resolutions for Specified Focal Lengths and Various Altitudes

This plot shows two important things. First, if the flyer can loiter at 250 meters, or below, for its entire mission, any focal length will give an acceptable resolution. Therefore, the shortest focal length, giving the largest coverage area and requiring the least weight and volume, can be used. Second, if the flyer is above 3000 meters of altitude, there is no focal length that will give a resolution below one meter. Therefore, in order to satisfy the one meter resolution requirement, the flyer must loiter at an altitude below 3000 meters above the object to be observed.

Figure 9 is a plot of how the resolution for various focal lengths changes with altitude.

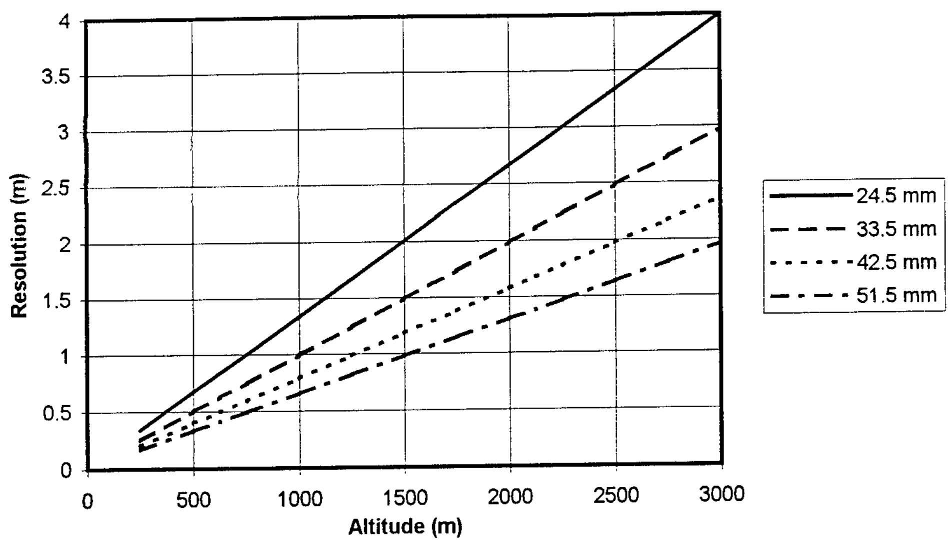


Figure 9: Sensor Resolution for Four Selected Focal Lengths Over a Small Range of Altitudes

The purpose of this plot was to represent the scenario where the flyer is initially deployed at an altitude above the point where the sensor has one meter resolution. The flyer may gradually decrease in altitude to the one meter resolution point and below. Therefore, this plot shows how the resolution for four chosen focal lengths decreases as the altitude decreases. The four focal lengths were : 24.5 mm, 33.5 mm, 42.5 mm, and 51.5 mm. 24.5 mm was chosen for the low end because it met the one meter resolution for very low altitudes, and then it showed the significant deviation from this level of resolution at relatively low altitudes. 51.5 mm was chosen for the high end because it was anticipated that the flyer may not be able to carry a focal length of much greater than 5 cm due to volume constraints. 33.5 mm and 42.5 mm were chosen to give evenly-spaced points on the plot between the low and high end focal lengths. This plot shows that beyond 1500 meters, not one of the focal lengths meets the resolution requirement. At 1500 meters, the 51.5 mm focal length gives almost exactly one meter resolution, but none of the smaller focal lengths can achieve this resolution at such a distance. Also, at 1000 meters of altitude and below, the 33.5 mm focal lengths and higher all meet the resolution requirements. Additionally, the 24.5 mm focal length does not meet the resolution requirement above 750 meters of altitude.

Using these three plots, a scenario for the flyer was envisioned in order to develop a preliminary propulsive power requirements analysis. The 33.5 mm focal length is a reasonable size to fit within the 5 inch artillery shell. This focal length achieved three meter resolution at 3000 meters of altitude and one meter resolution at 1000 meters of altitude. Therefore, it was envisioned that the flyer would use a sensor of 33.5 mm focal length and glide from 3000 meters of altitude to 1000 meters of altitude, where it would remain for an extended period of time. The gliding period could produce lower resolution pictures, but with a wider field of view, to help better determine exact areas where reconnaissance information is desired. At 1000 meters of altitude, the flyer would begin to loiter by turning on the propulsion system. This loiter altitude seemed reasonably high so that the flyer would be difficult to see with the naked eye, yet the resolution requirements could be met. Therefore, the propulsive power requirements were based on attempting to keep the flyer at straight, level flight at this altitude. It was noted that the flyer may be audible at this altitude. This is certainly possible if small internal combustion engines are used; however, the sound effects of these engines were not analyzed or planned for during this first semester of research. These effects will be realized when the engine is tested in the summer of 1997. Therefore, the possible loudness of the flyer was not considered to be a significant deterrent at this point.

A point to keep in mind is that the Xybion sensor may not even be used on WASP. However, if this is the case, the analysis of the Xybion sensor is not wasted. Rather, it shows important relationships between loiter altitude, field-of-view, focal length, and resolution that can be applied to many other vision sensors that might be used.

Other than the desired one meter resolution for WASP, the remaining customer requirements did not drive the initial calculations for the on-station propulsion system. The sensor set the flying altitude, and the lift, drag, and weight estimates set the propulsive power requirements. Based on these power requirements, "off the shelf" engines and motors that might fit this application could be investigated.

3.2 Quantitative Analysis of On-Station Propulsion Requirements

When this analysis was performed, no specific conceptual designs for WASP existed. Therefore, various combinations of wingspans, chord lengths, weights, and drag coefficients were analyzed. The relative effect of each of these parameters was determined, and a range of power requirements was then generated. Based on the results of this analysis, the author could begin to size engines and determine the validity of various propulsion systems without the need for conceptual system designs.

Performing this analysis without the benefit of WASP conceptual designs was valuable to the pace at which the project was able to progress. By performing a complete investigation and comparison of multiple methods of providing propulsive power, the best propulsion options for various WASP concepts could be decided quickly during the conceptual design process.

First, a range of possible wingspans and chord lengths was established for the WASP flyer. For the low estimate of the wingspan, approximately twice the artillery shell's length was used in order to represent the two wings running the length of the shell side-by-side and then deploying to 90 degree angles to the shell's longitudinal axis. For this estimate, no folding or complex deployment schemes for extra wingspan were assumed. For the low estimate of the chord length, 6 cm was used because it is approximately half of the shell's diameter. Together, these parameters gave the flyer a low-end wing area, S, estimate of 0.051 m^2.

For all cases, the coefficient of lift for the flyer was held constant at 1.2. This value was decided upon after a conversation with Professor Mark Drela. In this discussion, he stated that he felt that a lift coefficient of 1.2 was the best that could be achieved by any configuration of WASP flyer. However, the lift to drag ratio for the flyer could be changed by varying the drag coefficient. The drag coefficient could not simply be set, as the lift coefficient was. Rather, a test range of drag coefficients was determined by looking at drag coefficients for existing aircraft of different types, ranging from small general aviation aircraft to large cargo aircraft and passenger jets. Values from Table 6-4a of *The Design of the Aeroplane* were used for the drag coefficients, which

ranged from 0.05 for a relatively sleek aircraft to 0.07 for a relatively inefficient aerodynamic design [15].

The exact mass of the flyer was also unknown at the time of these calculations. However, the concept of using a composite shell was discussed. Preliminary analysis showed the mass of such a shell could be less than 20 kg. Also, the flyer may be much less in mass than the shell, and it may deploy from inside the shell. Therefore, a range of masses from 5 kg to 17 kg was used to determine a range of propulsive power required for the flyer.

The required propulsive thrust for straight, level, unaccelerated flight for each case was calculated by requiring that the net thrust produced must be equal to the aircraft's drag. At the same time, the lift generated by the aircraft must be equal to the aircraft's weight. Combining these two requirements leads to the following requirement for straight, level, unaccelerated flight [16].

$$T_R = \frac{W}{\left(C_L/C_D\right)} = \frac{W}{\left(L/D\right)} \tag{3.3}$$

The power required for a given thrust level is then determined by the thrust required multiplied by the flight velocity at that thrust level [16].

$$P_R = T_R V_\infty \tag{3.4}$$

Therefore, the flight velocity at the calculated thrust level needed to be determined. By using the definition of the lift coefficient, the flight velocity could be easily determined [16]:

$$V_\infty = \sqrt{\frac{W}{\frac{1}{2}\rho C_L S}} \tag{3.5}$$

Two plots were created using this analysis. The first plot, Figure 10, shows the power required for the range of possible flyer masses for the low-end wing area of 0.051 m^2, an increased wing area by 20% (0.0612 m^2) and an increased wing area by 40% (0.0714 m^2).

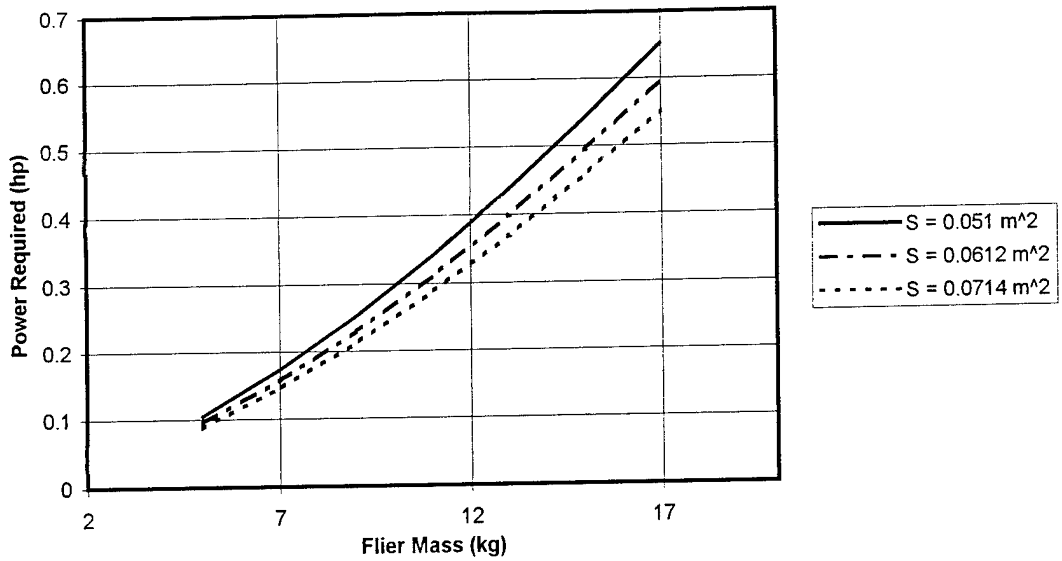


Figure 10: Power Required for Different Flyer Masses and Wing Areas

The second plot, Figure 11, shows the power required for the range of possible flyer masses for the low-end drag coefficient of 0.05, an increased drag coefficient by 20% (0.06) and an increased drag coefficient by 40% (0.07).

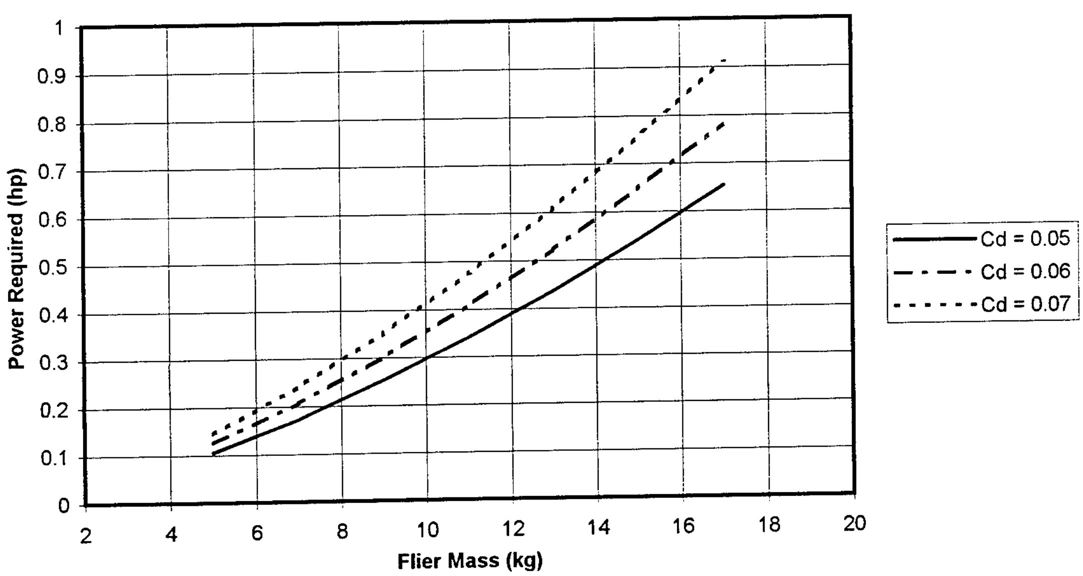


Figure 11: Power Required for Different Flyer Masses and Drag Coefficients

These two plots displayed an interesting result. By comparing Figures 10 and 11, it became clear that the power required calculation was more susceptible to changes in the drag coefficient then changes in the wing area. For example, an increase of 20% in the wing area resulted in the power required decreasing by an average of 0.05 hp (for a flyer mass of 17 kg). A decrease in the drag coefficient of 20% resulted in the power required decreasing by an average of 0.13 hp (for a flyer mass of 17 kg). This susceptibility also increases as the weight of the flyer increases, meaning that for heavier masses, an increase in the drag coefficient of 20% has a larger effect on the power required than an increase in the wing area of 20% when compared to the difference in power required for smaller flyer masses. At a flyer mass of 5 kg, the difference between the powers required is nearly negligible at approximately 0.01 hp. Figure 12 was created to display this effect.

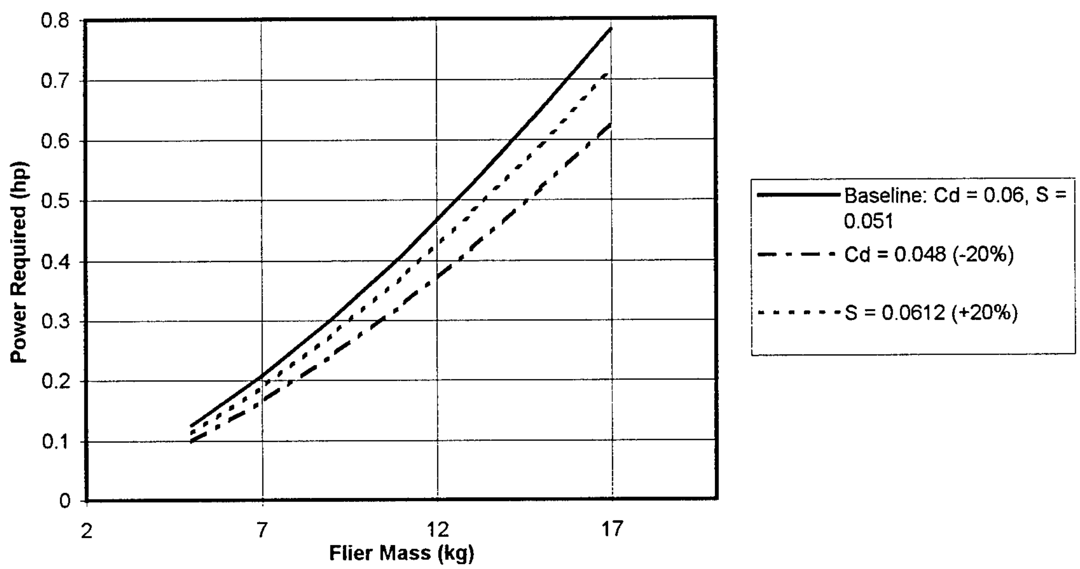


Figure 12: Power Required for Different Flyer Masses Showing the Relative Effects of Changing Wing Area and Drag Coefficient

Figure 12 shows that for designs with masses greater than 10 kg, choosing the correct drag coefficient range becomes very important. Beyond this mass, the difference between the power required for the low and high end drag coefficient estimates is greater than 0.1 hp, which is significant for engines of this size because it can result in large differences in system volumes. At a flyer mass of 17 kg, the power requirements differ by 0.26 hp for the high and low drag estimates. Therefore, when doing the conceptual designs for WASP, a conscious effort must be

made to determine drag coefficients for the concepts so that the resulting propulsion system can be determined.

This initial analysis was valuable to the project in two ways. First, all calculations were performed on spreadsheets so that the numbers can be manipulated at a later time, in case large changes occurred, such as the decision to use a different sensor. Second, this analysis gave the propulsion sub-group a range of powers for which to begin to size propulsion systems. The range investigated for a variety of propulsion methods, based on the values in Figures 10 through 12, was 0.1 hp to 0.9 hp.

3.3 Propulsion Conceptual Designs for WASP

The project team met frequently in early January of 1997 in order to brainstorm possible methods for developing the different subsystems that WASP would require. During one session, the team stated nearly twenty different ways of providing propulsive power to the flyer. At a later time, the feasibility of each of these possibilities was considered, and the list was down-sized to contain only those propulsion methods that met the requirements for low cost, small size, and the potential to survive the high-g environment, as well as permit a demonstration within a one and a half year timeline. The four possibilities that resulted from this down-selection meeting are discussed in the next chapter.

Chapter 4 On-Station Propulsion Subsystem Options

4.1 Rocket Motors

Solid rocket motors are currently employed by high-g systems, such as the US Army's 155 mm rocket-assisted artillery shell. Therefore, rocket power was certainly an option that needed to be investigated for the WASP flyer due to rocket motors' ability to handle high-g's while keeping a relatively compact size. There were three types of rockets that were compared in order to determine if one type of rocket might be best for the WASP flyer application: liquid rockets, solid rockets, and hybrid rockets. Each of these systems is discussed in detail in *Space Propulsion Analysis and Design* [17]. The information provided in this publication was used to objectively compare the different types of rockets in order to determine which rocket would be best for the WASP flyer.

While aerospace engineers, in general, are familiar with solid and liquid rockets, most are not familiar with the design of hybrid rockets. Therefore, hybrid rocket design aspects will be the only design aspects discussed here. The hybrid rocket gets its name from the fact that the fuel and oxidizer are kept in different states, a liquid and a solid. Typically, the oxidizer is a liquid, such as liquid oxygen, and the fuel is a solid, such as Hydroxyl Terminated PolyButadiene (HTPB) [17]. However, "reverse hybrids" also exist where the oxidizer is a solid, and the fuel is a liquid [17]. For the analysis done here, a liquid oxidizer and solid fuel are assumed. Figure 13 is a schematic showing how a hybrid rocket system works [17]. The circled R represents a regulator between the pressurant and oxidizer tanks, and the circled V represents a valve between the oxidizer tank and combustion chamber.

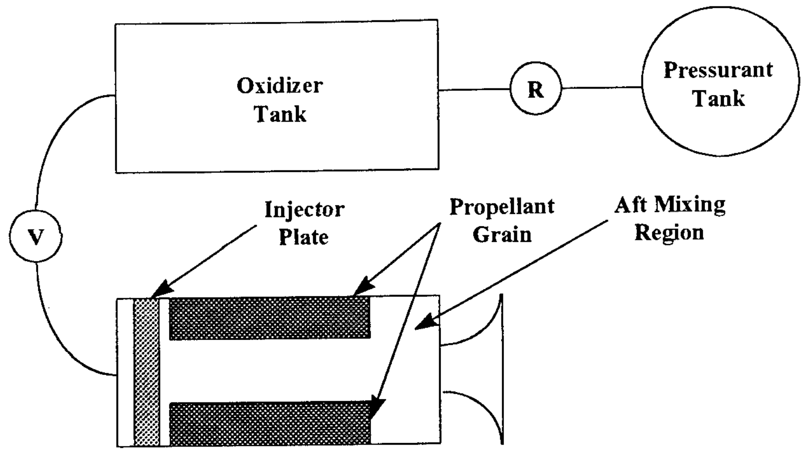


Figure 13: Hybrid Rocket System Drawing

A table similar to a Pugh Matrix was used in order to compare the liquid, solid, and hybrid rocket systems. A Pugh Matrix is a graphical method for comparing different options being considered in a design process. One option is chosen as a "baseline" configuration, and other options are given a "+" or "-" for various criteria to indicate whether or not an option is better or worse than the baseline option for a particular criterion [5]. For Pugh Matrices, unlike for Quality Function Deployment, no weightings are given to criteria. Weightings are specifically not employed because engineers tend to use the numbers as absolute, which is not the purpose of the Pugh Matrix. Rather, the Pugh Matrix helps engineers compare design options relatively based on chosen criteria [5].

For the comparison table used in this project, scores from one to ten were given for each of the rockets in each of the criteria, rather than simply using plusses or minuses. For all criteria, a score of ten reflected a great ability for a rocket to perform a particular criterion. A score of one reflected a rocket's inability to satisfy a particular criterion. Highlighted sections of the table display the reason, or reasons, that a particular rocket was not selected for the WASP flyer.

The comparison criteria used to compare the different rockets were derived from the customer requirements. First, the total complexity of each type of system was rated relatively. Scores from one to ten were given to each of the rocket types based on the number of regulators, feed lines, pumps, valves, and other components required. A higher score reflects a lower system

complexity. The system complexity measure was chosen for this comparison because it addresses the question of how difficult the design of a particular rocket would be for g-hardening to high-g's on a small scale. Second, total rocket system costs were compared relatively. This measure was chosen in response to the requirement for a total system cost of less than $20,000. A high score reflects a system's lower cost. Third, the "extensibility" of each type of rocket was rated. This category included such things as re-start capability, throttling capability, as well as environmental robustness for each system. A higher score reflects greater extensibility. Fourth, the level of innovation required versus the amount of a rocket system that can be taken as "off-the-shelf" was compared. This measure was chosen due to the short, one and a half year timeline for the project. This amount of time simply does not allow for a tremendous amount of new invention for a propulsion system. A higher score reflects the need for less invention in order to develop a working system. Fifth, the relative system size for each rocket type was compared. For the WASP flyer, volume is precious because the useable volume within a five inch artillery shell is quite small. Therefore, the relative measure of a rocket system's compactness, or ability to be compacted, is helpful in choosing a system. A higher score in this category reflects a higher ability for a rocket to be "compacted."

Table 9 is the table that resulted from this analysis. There were three main reasons for eliminating the liquid rocket. First, the liquid rocket is a very complex system, requiring multiple regulators, valves, tanks, and pumps. For a small scale application, this complexity becomes even greater. Second, liquid rockets are not currently used for WASP-type applications. A great deal of innovation would be required in order to develop a small system that would withstand high-g's. Third, of the three rockets considered, liquid rockets required the greatest amount of volume to accomplish a desired thrust.

The reason for eliminating the solid rocket and choosing the hybrid rocket was not as evident. The fact that solid rockets are currently used in high-g applications makes them an attractive choice; however, the final decision came down to a question of extensibility. The hybrid rocket is very safe due to the fact that the oxidizer and fuel are in separate states, can be throttled during

operation, and has the ability to shut off and re-start during operation. Solid rockets cannot do any of these, and therefore, the hybrid rocket was more attractive for the WASP application.

Table 9: Rockets Systems Comparison Table

Rating / Parameter / Rocket Type	System Complexity 0-10		System Cost 0-10		System Extensibility 0-10		COTS / Invention 0-10		Relative System Size 0-10	
Liquid Rocket	3	most complex system: multiple regulators, valves, tanks, and pumps	4	liquid rockets not used for applications close to ours, added to high complexity makes system expensive	8	has re-start capability, but system must be handled carefully	2	liquid rockets are not currently used for WASP-type missions: much innovation would be required	3	liquid rockets are the largest of the three systems due to the many required parts for the complete system
Solid Rocket	10	least complex system: complete system contained in one single case	7	relatively low cost due to low complexity; inability to test each system makes initial design more expensive	4	does not have re-start capability, and must be handled carefully due to failure susceptibility from cracks in the solid fuel	6	solid rockets are the current choice for WASP-type applications, involving high-g's and small size	7	solid rockets are the most compact of the three rocket types
Hybrid Rocket	7	somewhat complex: fuel grain and containment is simple, but liquid oxidizer and pressurant tank must be used	10	lower system cost results from reduced failure modes due to possible use of commercial-grade ingredients	10	has re-start capability, and it is safe to handle due to oxidizer and fuel being in two separate states; hybrids can also be throttled	4	hybrid rockets of the desired size and thrust have been produced, but they have not been g-hardened	6	hybrid rockets have fairly compact designs that will fit into artillery shells, but they are not as compact as solid motors

* Note: Shaded areas indicate reasons for elimination of a rocket

Once the decision was made to look at hybrid rockets for possible use in the WASP flyer, a preliminary design was performed in order to determine the actual size of the system that would be required. The design process discussed in *Space Propulsion Analysis and Design* was used for this sizing [17]. All calculations for this preliminary design were performed using a MathCAD worksheet, which is provided in Appendix D. Quantities that had to be solved for by iteration, such as exit Mach number, were calculated using Excel, and then the values were input into the MathCAD worksheet manually.

The system requirements, including initial mass, payload mass, thrust-to-weight ratio, ΔV, nozzle expansion ratio, and chamber pressure, had to be chosen first in order to begin the design process. These values were selected as follows:

$$M_{initial} = 15 \text{ kg}$$
$$M_{payload} = 5 \text{ kg}$$
$$F/W = 0.3$$
$$\Delta V = 100 \text{ m/s}$$
$$\varepsilon = 30$$
$$P_{chamber} = 7 \text{ MPa}$$

Using these chosen quantities, the preliminary design process was conducted. The resulting system consisted of the following component sizes:

Pressurant Tank: 8.89 cm diameter, 1.651 cm height

Oxidizer Tank: 8.89 cm diameter, 4.93 cm height

Thrust Chamber: 4.39 cm diameter, 17.12 cm height

Bell Nozzle: 2.13 cm diameter, 2.13 cm height

Total System Volume: 811.92 cm^3

Total System Mass: 1.36 kg

The total system volume was calculated by summing the volumes for the individual components and adding 20% for the rocket's structure. Based on the numbers above, the energy density for the hybrid rocket, ED_{Hybrid}, in $W \cdot hrs/cm^3$, was calculated in order to use in comparison with other propulsion methods that will be investigated later. The following equation was used for this calculation:

$$ED_{Hybrid} = \frac{F \cdot \upsilon \cdot t_{flight}}{V_{Hybrid}} \tag{4.1}$$

Where F is determined using the following unit conversion:

$$F = M_{initial} \cdot F/_W \cdot g_0 \tag{4.2}$$

and $g_o = 9.807 \ \frac{\text{m}}{\text{sec}^2}$.

The υ in equation 4.1 is the flight velocity of the rocket. For this number, the ΔV of the rocket was used. As the MathCAD worksheet shows, the flight duration for the hybrid rocket is quite small ($t_{flight} = 16.72$ seconds). However, the system is also greatly over-powered. Therefore, this rocket would be throttled to run at a lower power setting for a longer period of time, but the MathCAD-calculated power output and flight duration were used for the energy density calculation. The resulting energy density for the hybrid rocket was $0.0252\ W \cdot hrs/cm^3$. An AutoCAD drawing of the hybrid rocket for WASP is shown below The dimensions for this drawing are given in the text above.

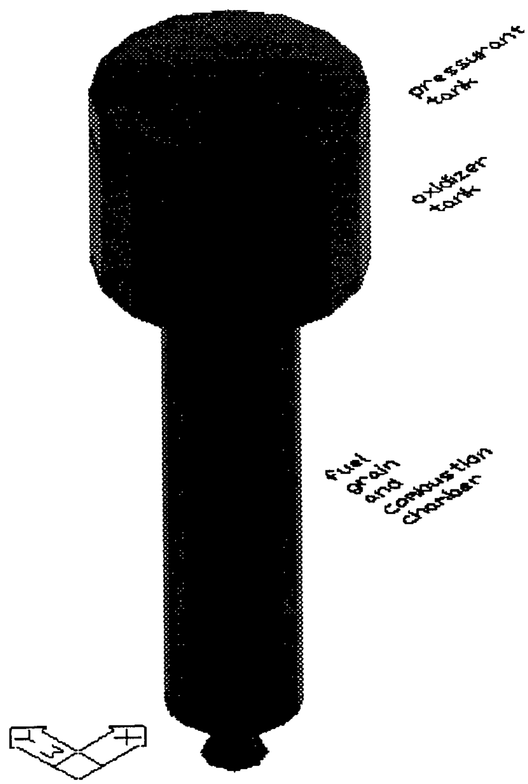


Figure 14: AutoCAD Drawing of WASP Hybrid Rocket

4.2 Electric Motor

Initially, electric motors seemed to be a very good choice for the propulsion system for WASP. It was thought that electric motors would be easier to g-harden than all other options being considered for two reasons. First, the system is simple, requiring only a battery and a motor. If a thermal battery is used, no motor controller is needed. The motor will simply run until the thermal battery dies. Thermal batteries are already used in high-g systems, and their design actually makes them inherently g-hardened. The second reason electric motors were initially attractive is due to the fact that the motor only has one moving part. By designing a g-hardened housing for the motor, as well as a support for the shaft, it was believed that the electric propulsion system would be able to survive the high-g environment. These thoughts were confirmed by MIT graduate and CEO of Kress Jets, Inc., Bob Kress, during a telephone conversation [18]. He felt that it would be possible to use a brushless electric motor for WASP's application because brushless motors spin the permanent magnets on the rotor, rather than the copper windings. This type of construction may facilitate g-hardening. As an added advantage, brushless motors also have higher efficiencies than conventional electric motors.

For further research into electric motors for the WASP application, Bob Kress referred the team to Dave Polumbo, CEO of Aveox, the largest seller of brushless electric motors for remote-controlled aircraft in the United States. A discussion with Mr. Polumbo showed that electric motors are an option that works in theory, but the state-of-the-art is not to the point where this option becomes a better choice than internal combustion engines [19]. The remainder of this section shows how the relatively low energy density of electrical systems results in their being difficult to incorporate in the WASP flyer.

Brushless motors for radio-controlled aircraft that span the entire range of propulsive power required from Section 3.2 are currently available. Specific motors from the Aveox Home Page that met the propulsive power requirements for WASP were compiled into the table below [20]:

Table 10: Possible Brushless Motors for WASP

Comparison Parameter / Motor Model	Weight (kg)	Length (cm)	Diameter (cm)	Volume (cm^3)	P_{output} (hp)
1406/2Y	0.196	4.47	3.73	48.84	0.337
1409/2Y	0.247	5.23	3.73	57.15	0.569
1412/2Y	0.289	5.99	3.73	65.45	0.520
1415/2Y	0.347	6.76	3.73	73.87	0.885

This table shows that there are relatively compact motors that can produce gas-powered-like levels of horsepower. However, the problems associated with using the electrical propulsion system in the WASP flyer do not stem from the motor sizes, but rather the total energy required to run the motors for the desired time of powered flight. Brushless motors typically have efficiencies of 70% to 85%, which means that 70% to 85% of the input power to the motor is realized in the motor's output [20]. Assuming that the propeller will have an efficiency of 85% and the motor will have an efficiency in the middle of the range listed above (77.5%), the actual electrical propulsion system power realized by the aircraft is approximately:

$$P_{out} \approx 0.659 \cdot P_{in} \tag{4.3}$$

If P_{in} is given in Watts, P_{out} can be converted to horsepower from:

$$P_{out}(hp) = \frac{P_{out}(W)}{746\ W} \tag{4.4}$$

Using equations 4.3 and 4.4 to solve for the required input power to the motors in Table 10 gives a range of input powers from 381 W to 1002 W.

The size of these required powers is realized when one attempts to size batteries for the system. The required currents for the motors are approximately between 30 A and 50 A. Considering that other electrical components on the flyer, such as the GPS Processor, require currents of less than 1 A, the required current level of the motors becomes extremely difficult to achieve for any long period of time. For electrically-powered radio-controlled aircraft, the typical run-time is approximately five to seven minutes due to the high current levels that the motors require. Not

only are the NiCd batteries used to power these systems too large for the 5 inch artillery shell, but they would not even allow the motor to run for ten minutes of the desired loiter time.

Before eliminating the possibility of using electric propulsion, the team needed to confirm that no batteries existed that would meet the motors' requirements. For questions concerning high-g battery and power systems, Carlo Venditti at the Draper Laboratory was contacted [21]. Venditti provided the team with two manuals produced by Eagle-Picher Industries, Inc. Eagle-Picher is the largest known producer of high-g primary, reserve, and thermal batteries, some of which have flown on Draper high-g experiments, such as the Extended Range Guided Munition (ERGM). From these manuals, it was found that no primary or reserve batteries exist that are constructed to deliver a current close to 30 A, and most of the currents were less than 1 A for these types of batteries [22]. Only two batteries even came close to meeting the power requirements for the electric motors, and they are given in the table below [22].

Table 11: High-Rate Primary and Reserve Eagle-Picher Batteries

Battery Name	Approx. Run Time (minutes)	Battery Weight (kg)	Battery Volume (cm^3)
LCF-111	7	0.88	570
MAP-9233	1.5	0.465	119.95

Some thermal batteries were found that might possibly meet both the current and voltage requirements for the motors, but the batteries' sizes were simply too large for the 5 inch shell [23]. If the battery were to fit in the shell, then insufficient room would remain for the remaining electrical components, as well as the wings and tail. These batteries, and their sizes, are listed in Table 12 [23].

Table 12: High Rate Thermal Eagle-Picher Batteries

Battery Name	Approx. Run Time (minutes)	Battery Weight (kg)	Battery Volume (cm^3)
EAP-12129	5	0.48	217.95
EAP-12124	1	0.232	62.76
EAP-12100	5	2.159	742.33
EAP-12099	5	1.545	586.66
EAP-12051	10	1.78	662.2
EAP-9254	2.8	0.15	102.96

Based on the numbers above, the energy density for the electric propulsion system, $ED_{Electric}$, in $W \cdot hrs/cm^3$, was calculated in order to use in comparison with other propulsion methods. For this calculation, the EAP-12051 thermal battery was chosen because it was the only battery that was believed to provide enough power to run the electric motor for the desired ten minute mission. The estimated run time for this system was based on a voltage 14 V and a current of 19.7 A, which results in a battery output power, or motor input power, of 276 W. Using equation 4.3, the output power of the motor that would be realized by the aircraft is approximately 182 W, or 0.244 horsepower. The following equation was used for the energy density calculation:

$$ED_{Electric} = \frac{0.659 \cdot P_{battery} \cdot t_{flight}}{V_{Electric}} \tag{4.5}$$

For the volume of the electric propulsion system, $V_{Electric}$, the 1406/2Y motor from Table 10 was chosen because the achievable output for the battery is less than the maximum power that the 1406/2Y can produce. Therefore, the 1406/2Y is of sufficient size to handle the battery's output, and the motor requires the smallest volume of any of the motors in Table 10 (48.84 cm^3). The electric motor is designed to turn an eight inch diameter propeller. For the calculation of the propeller volume, the propeller was assumed to be a thin, long cylinder with a length of 8 inches (20.32 cm) and a diameter of 0.75 inches (1.905 cm). This assumption led to a propeller volume, V_{prop}, of 3.534 in^3, or 57.92 cm^3. The following equation was used to determine the total electric

propulsion system volume, where the 1.15 represents an adding of 15% to the volume for structural supports:

$$V_{Electric} = 1.15\left(V_{Battery} + V_{Motor} + V_{prop}\right) \tag{4.6}$$

The resulting electric propulsion system volume was 884.3 cm^3. Therefore, the energy density of the electric propulsion system was 0.0343 $W \cdot hrs/cm^3$.

Before eliminating the electrical propulsion system from consideration at this point due to battery concerns, a telephone call was made to confirm the team's findings. Ron Noviln, an employee of Eagle-Picher's marketing department was contacted, and the power requirements of the electric motors were given to him [24]. After discussing these requirements with employees of the thermal battery department, Mr. Noviln confirmed the team's findings. No batteries currently exist that have the necessary high rate of power output in the compact size required. Therefore, it could be stated that the energy density of the electrical system is simply insufficient for the WASP flyer's purposes. At this point, an electrical propulsion system was eliminated from consideration.

4.3 Wankel Rotary Engine

The idea to use a small, Wankel rotary engine for propulsive power for the WASP flyer came from John Elwell at the Draper Laboratory in *System Requirements*, published 2 January, 1997 [7]. Elwell referred the team to David Liese, an employee of Dahlgren, who had been interested in using the Wankel engine in the Navy's Longlook concept, which was also a UAV that deployed from a 5 inch artillery shell. In an article published in the May/June, 1996, issue of *Surface Warfare*, a claim was made that by using a small Wankel engine, the Longlook flyer could stay on-station for three hours while being only the size of a large crow [25]. Certainly, based on this information, the Wankel engine was worth researching for the WASP flyer application.

Liese pointed the team in the direction of a web page where the Longlook team acquired much of its information about the small Wankel engine. The OS Engines "30 Wankel" is a 0.303 cubic inch displacement "glow engine" that produces 1.27 brake horse power at 17,000 RPM [26]. The engine is 2.775 inches in diameter (7.0485 cm) and 2.59 inches in length (6.5786 cm) while weighing 11.8 oz (0.335 kg) [26]. Its fuel consumption rate is listed at approximately 19.72 cm^3

per minute [27]. Therefore, the desired ten minute mission would require 197.2 cm^3 of fuel. The OS Engines Wankel is the only existing Wankel engine of this size, though other Wankel engines for radio-controlled aircraft do exist.

A total volume for the Wankel engine system was calculated using the engine dimensions and fuel requirements listed above. The following equation was used for this calculation:

$$V_{Wankel} = 1.15\left(V_{engine} + V_{fuel} + V_{starter} + V_{propeller} + V_{muffler}\right) \tag{4.7}$$

The engine volume, V_{engine}, was determined by approximating the engine as a cylinder with length of 6.5786 cm and a diameter of 7.0485 cm (V_{engine} = 256.7 cm^3). The fuel volume, stated above, was 197.2 cm^3. The starter volume was simply an estimate. There are currently no remote starter systems made for engines of this size; however, remote starters do exist for engines of 0.40 cubic inches and larger. The assumption used for the starter was that a small electric motor would be geared to the engine's crankshaft and turned over after the glow plug was lit. It was also assumed that the electric motor would not require an additional battery. Rather, for a period of seconds, it would use power from the battery used for the sensor and processors. The starter motor was assumed to be 1.5 inches long (3.81 cm) and 1 inch in diameter (2.54 cm), which gave a starter motor volume, $V_{starter}$, of 1.178 in^3, or 19.31 cm^3. The Wankel engine is designed to turn a 9 inch diameter propeller. For the calculation of the propeller volume, the propeller was assumed to be a thin, long cylinder with a length of 9 inches (22.86 cm) and a diameter of 0.75 inches (1.905 cm). This assumption led to a propeller volume, V_{prop}, of 3.976 in^3, or 65.156 cm^3. The muffler volume, $V_{muffler}$, was calculated by assuming the muffler to be a cylinder with 1 inch diameter (2.54 cm) and 1.5 inch length (3.81 cm). These estimates gave a muffler volume of 1.178 in^3, or 19.31 cm^3. The last volume that was included in the total Wankel system volume was the estimated amount of inert mass that would be added to the system for structure. It was assumed that the Wankel system would be a complete system, held in one unit, that would be connected to a substructure inside the shell. The additional volume that would be required to make the Wankel system into a single unit was assumed to be 15% of the already calculated volume, thus giving rise to the 1.15 in equation 4.7. The total Wankel system volume, V_{Wankel}, that resulted from the estimates above was 39.14 in^3, or 641.3 cm^3.

Using this volume, an estimate was made of the energy density, of the Wankel system, ED_{Wankel}, in $W \cdot hrs/cm^3$ using the following equation:

$$ED_{Wankel} = \frac{0.85 \cdot BHP_{Wankel} \cdot \dfrac{746\text{ W}}{1\text{ BHP}} \cdot t_{flight}}{V_{Wankel}} \tag{4.8}$$

The brake horsepower of the engine, BHP_{Wankel}, is 1.27. Multiplying this by the propeller efficiency used in the electric motor calculations (85%) gives an actual output of 1.0795 hp, or 805.3 W, that is realized by the aircraft. The system will fly for 10 minutes, or one-sixth of an hour, given the amount of fuel estimated earlier. Therefore, the energy density of the Wankel system is approximately 0.2093 $W \cdot hrs/cm^3$, which is nearly one order of magnitude higher than that calculated for both the electric and rocket propulsion options.

As will be shown in the next section, some two stroke engines are smaller than the Wankel engine, and they require less fuel to complete the ten minute mission; however, for a given engine displacement, the output power of two stroke engines, in general, is less than that of Wankel engines. There is a relationship that exists between two stroke and Wankel engines that is simply a product of their physics. For a given size displacement, a Wankel engine will not burn fuel as efficiently as a two stroke engine, but the Wankel engine will put out more power than the two stroke engine. Therefore, the decision between these two systems would seem to be whether the high power of the Wankel engine is needed or not. If the power is needed, than the Wankel engine would be the selection. If the large power output is not necessary, then the two stroke engine can do the same mission with less fuel, and therefore, a smaller total volume [28].

These findings were discussed with Jay Lipeless, an employee of Dahlgren who worked on the Longlook Project. First, the team wanted to understand Dahlgren's basis for deciding to use a Wankel engine, rather than a two stroke engine. Second, the team wanted to know how Dahlgren planned to use an aircraft the size of a "large crow" in order to achieve a three hour loiter time [29]. The team's preliminary sizing of all of the subsystems for the WASP flyer showed that it would be difficult to fit any more than the 197.2 cm^3 of fuel already allotted for the Wankel

engine. Also, the WASP flyer was already assumed to be larger than that of a crow. Therefore, the only way this system could achieve a longer loiter time would be if the engine's RPM's were lowered so that the engine would require less fuel. Of course, this change would come at the expense of output power as well. In any case, it seemed nearly impossible for this system to achieve a three hour loiter time.

The answers to these two questions that the team received were surprisingly in support of the estimates the team had made to this point. First, it was found that Longlook decided to use the Wankel engine not because of its high power output, but rather, because the Longlook team felt it would have a much better chance of surviving the high-g launch environment [29]. The Wankel engine only has one moving part, and that part rests against a flat plate during the launch. Therefore, Longlook concluded that it would take minimal or no design changes to incorporate the Wankel engine into an artillery shell. Mr. Lipeless stated that other engine types, may work in this environment as well, but they were simply considered "too risky," though apparently no formal testing was performed to determine the survivability of these systems in the harsh launch environment [29]. Therefore, for the WASP flyer, it was concluded that the Wankel engine should not be automatically assumed to be a better choice than two stroke engines. In an answer to the second question, Mr. Lipeless stated that the Longlook flyer was actually "bigger than a crow" [29]. The MIT / Draper team research led the team to believe that there was simply not enough room in an aircraft the size of a crow to carry everything that would be needed in order to keep the flyer aloft for three hours, such as more fuel, wing area, and tail area. Mr. Lipeless' statement suggested that this finding was correct. Therefore, it seemed logical for the team at this point to research the possibility of using a small two or four stroke engine.

4.4 Two and Four Stroke Internal Combustion Engines

A wide range of small two and four stroke engines for radio-controlled aircraft was researched. First, however, the method these small engines use to combust their fuel was examined. The engines used most-often are "semi-diesels," or what modelers call "glow engines" [30]. Like diesel engines, there is no spark required to ignite the fuel. However, the compressed gasses do need some added heat in order to combust, which comes from a platinum wire coil inside of a

glow plug [30]. The platinum wire coil is heated until red hot, the engine is started, and then electricity is no longer sent to the wire coil once the engine is started. Rather, the heat of the combustion process is enough to keep the wire coil at a high enough temperature to keep the combustion process going [30].

Before looking at specific engines, the relative advantages and disadvantages of two and four stroke engines were investigated in order to determine if one type of engine might be better for the WASP flyer application. It was found that for a given displacement, the four stroke engine has both a greater combustion mixture volume and a longer power stroke than the two stroke engine [30]. These advantages of the four stroke engine lead to its better fuel efficiency than two stroke engines. However, since the power stroke for a two stroke engine occurs every revolution, and the power stroke for a four stroke engine occurs once every two revolutions, a four stroke engine will only manufacture 60% to 75% the power of a two stroke engine for a given displacement [30]. Therefore, it would appear that if power per volume were the important factor in this design, then the two stroke engine would be the best choice. However, if fuel efficiency, and therefore longer loiter time, were the important factor, then the four stroke engine would appear to be a good choice.

There is one more significant factor that comes into play when deciding between a two and four stroke engine for the WASP flyer: system complexity. A two stroke engine has three moving parts: crankshaft, connecting rod, and piston. A four stroke engine has at least ten moving parts, which greatly complicates the system's design. Since a two stroke engine has less than half as many parts as a four stroke engine, the two stroke is both cheaper and easier to maintain [30]. For this reason, the four stroke option was considered to be much more risky than the two stroke option. Therefore, two stroke engines were investigated more closely for the WASP flyer, but the four stroke option was not eliminated.

Two companies which sell radio-controlled aircraft engines were contacted through a web search: Mecoa and MNC Hobbies. The power range determined in Section 3.2 was given to the companies, and small engine size as well as good fuel efficiency were stressed as being important

to choosing the engine for the WASP flyer. The companies replied, via email, with the three engines listed in Table 13 [31 & 32].

Table 13: Possible Engines for WASP Flyer From Mecoa and MNC Hobbies

Manufacturer	Engine Name	Displacement (inches^3)	Horsepower	Fuel Consump. Rate (cm^3 per min)
RJL	Conquest 0.15 (2 stroke)	0.15	0.7	11.83
RJL	HP VT 0.21 (4 stroke)	0.21	0.35	3.94
Thunder Tiger	GP 0.15	0.15	0.42	7.40

Each of the engines above would cost between $50 and $75. Comparing the three engines above with each other was difficult because each engine would be best for a particular application. The Conquest 0.15 has the highest power output for a 0.15 cubic inch engine on the market, but fuel consumption rate suffers somewhat. The HP VT 0.21 has one of the lowest fuel consumption rates on the market for its size because it is a four stroke engine, but output power suffers somewhat, and the engine is significantly larger than the 0.15 cubic inch engines discussed here. The GP 0.15 has average output power for an engine of this size, and it also has an average fuel consumption rate. Because there was no specific WASP flyer concept to size an engine for at this point, all three engines were carried on to the next phase of the project: conceptual design. During the conceptual design phase, each of the engines would be analyzed to determine which engine would be best for certain designs.

However, in order to get an idea of the total system volume required, and therefore the energy density, *ED*, for the two and four stroke engines, a similar process to that discussed in Section 4.3 for the sizing of the Wankel system was performed for the Thunder Tiger GP 0.15. This engine was selected because it was basically the average of the three engines listed in Table 13. The total volume required for the RJL Conquest 0.15 would be greater because of its higher fuel consumption rate, and the RJL HP VT 0.21 would require the same or a smaller volume because of its lower fuel consumption rate but engine size itself is larger. Applying equation 4.7 to the two stroke engine gave the following equation:

$$V_{TTiger} = 1.15\left(V_{engine} + V_{fuel} + V_{starter} + V_{propeller} + V_{muffler}\right) \tag{4.9}$$

Using information provided by the engine manufacturer, Thunder Tiger, USA, the engine volume, V_{engine}, was calculated to be 83.31 cm^3 [33]. The fuel volume required, V_{fuel}, based on the fuel consumption rate given in Table 13, was 74 cm^3. The propeller volume required for the Thunder Tiger engine, $V_{propeller}$, was assumed to be the same as that of the electric motor (57.92 cm^3), since this engine is designed to turn a propeller that is slightly smaller than that to be used by the Wankel engine. Both the starter and muffler volumes required were assumed to be the same as that required for the Wankel engine (both were 19.31 cm^3). These estimates resulted in a total system volume, V_{TTiger}, of 291.9 cm^3.

Using this calculated system volume, the energy density for the two stroke system, $ED_{2stroke}$, was calculated using the following formula:

$$ED_{2stroke} = \frac{0.85 \cdot BHP_{2stroke} \cdot \dfrac{746\ \text{W}}{1\ \text{BHP}} \cdot t_{flight}}{V_{TTiger}} \tag{4.10}$$

This calculation resulted in an energy density for the two stroke system of 0.1521 $W \cdot hrs/cm^3$, which is much higher than the electric and rocket options, but only about 75% as high as the Wankel option. Once this calculation was completed, the down-selection process began, where each of the concepts discussed in Section 4.1 through 4.4 were compared using various criteria. This selection processed is discussed in Section 4.5.

4.5 Propulsion Subsystem Down Selection

A table similar to the comparison matrix used in Section 4.1 to compare different types of rocket systems was developed in order to compare the four different propulsion options that were investigated. As for Table 9, scores from one to ten were given for each of the propulsion options in each of the criteria. For all criteria, a score of ten reflected a great ability for a propulsion system to perform a particular criterion. A score of one reflected a propulsion system's inability to satisfy a particular criterion. Highlighted sections of the table display the reason, or reasons, that a particular system was not selected for the WASP flyer.

The criteria used to compare the different propulsion systems were derived from the customer requirements, as well as the project constraints, such as the fact that the propulsion system and all other components must be able to fit into a five inch artillery shell. First, the total complexity of each type of system was rated relatively. Scores from one to ten were given to each of the propulsion systems based on facts about each system, such as the number of moving parts, system components, valves, regulators, and tanks required. A higher score reflects a lower system complexity. The system complexity measure was chosen for this comparison because it addresses the question of how difficult the design of a particular system would be on a small scale. Second, total propulsion system costs were compared relatively. This measure was chosen in response to the requirement for a total system cost of less than $20,000. A high score reflects a system's lower cost. Third, the energy density of each system was rated. This criterion reflected a system's ability to efficiently provide propulsion for the WASP flyer. A higher score reflects a higher energy density. Fourth, the level of innovation required versus the amount of a propulsion system that can be taken as "off-the-shelf" was compared. This measure was chosen, as stated in Section 4.1, due to the short one and a half year timeline for the project. A higher score reflects the need for less invention in order to develop a working system. Fifth, the relative system size for each of the propulsion systems was compared. Though no weightings were given to any of the criteria, this criterion may be the most important. If it would be difficult to fit a particular system in the five inch shell, the other merits of that system would be negated because whether or not it had the highest energy density, or lowest system cost, would no longer matter. The system absolutely must fit into the room allotted in the shell. Therefore, the relative measure of a system's compactness, or ability to be compacted, is very important in determining a propulsion system for the WASP flyer. A higher score in this category reflects a propulsion system's lower total volume.

Table 14 is the result of this analysis. A shaded box indicates a "show-stopper" for a particular propulsion option. There were three main reasons for eliminating the electric motor. First, the electric motor had a very low energy density in comparison to the two stroke and Wankel engine options. This low energy density led to the second reason for the electric system's elimination:

large system volume. The electric propulsion system simply required a very large volume, while its output was less than that of other options, such as the Wankel and two stroke options. Third, a battery would have to be specifically designed for this application. No batteries currently exist that meet the high-g, high-rate requirements of the electric motor.

There are four reasons highlighted in Table 14 why the hybrid rocket was eliminated. First, it is the most complex of any of the systems, with the need for very small, g-hardened regulators, valves, and feed lines. This level of complexity was determined to be too significant to deal with on this project. Second, since no production models of hybrid rockets currently exist, the entire system would have to be developed from scratch, which leads to the third reason for the hybrid rocket's elimination: high system cost. Fourth, the hybrid rocket requires the greatest volume of any of the four systems researched. This volume requirement is a result of the need for the hybrid rocket to carry its oxidizer and pressurant on-board the flyer, whereas the two stroke and Wankel engines simply use the air as their oxidizers.

The reason for the elimination of the Wankel engine, and the decision to use a two stroke engine is not as obvious as for the other systems. The final decision between these two systems came down to a comparison of the system sizes. Due to the Wankel engine's higher fuel consumption rate, it required more fuel than the two stroke option. Obviously, the power on the Wankel could have been turned down to a level comparable to that of the two stroke (0.42 hp), thus saving on fuel somewhat. However, at this power level, the Wankel engine still requires more fuel than the two stroke option. Total volume for the Wankel engine system was calculated at 641.3 cm^3, as compared with a total two stroke engine system volume of 291.9 cm^3. Therefore, since the two stroke system volume is less than half the Wankel volume, it was decided that the two stroke engine was the team's first choice for a propulsion system. The Wankel engine would remain as a fall-back choice. If testing of the two stroke engine resulted in a reason to eliminate the two stroke option that was not considered prior to this decision, then testing of the Wankel Engine for the WASP flyer would begin.

Table 14: Propulsion Systems Comparison Table (shaded areas indicate reasons for elimination)

Rating / Parameter / Propulsion System	System Complexity 0-10		System Cost 0-10		Power per Volume 0-10		COTS / Invention 0-10		Relative System Size 0-10	
Electric Motor	10	simple system requiring only a g-hardened battery connected to the motor; motor controller not necessarily required	4	motor is inexpensive, but battery required would cost at least $3500, and it would have to be newly developed	2	the energy density of this system is the lowest of the possible systems	2	current electric motors for R/C aircraft may be able to withstand high g's, but a battery would have to be specifically designed for this application	2	electric motor is very compact, but the power required is significant enough to require a large battery which makes the total system volume greater than that of the gas powered engines
Wankel Engine	7	potentially more simple than 2/4 stroke engines due to greater g-hardening ability; shaft at center of engine leads to more simple design	7	engine is approximately $280; other significant costs include development of starter system, fuel tank, and system hardening	6	of the gas powered options, this system has the highest power output per volume	7	the wankel engine may be able to withstand high-g's as it is currently designed; a starter system would have to be designed	3	relatively small engine, but fuel inefficiency is more than twice that of 2 stroke engines, which leads to the requirement for a larger fuel tank in order to meet the loiter time requirement
Hybrid Rocket	2	most complex system, including a solid fuel chamber, oxidizer tank, pressurant tank, and feed lines running between these components	2	this system would have to be almost entirely a new design; expected cost would be over $4000 per unit	3	power per volume at this scale is approximately 1/2 that of the gas powered engines	1	this entire system would have to be developed; not many production models of hybrid rockets currently exist	1	volume required is approximately three times that of 2/4 stroke engines because of the requirement for oxidizer and pressurant tanks
2/4 Stroke Engine	6	more simple than a rocket engine, but potentially difficult to g-harden; like the wankel engine, another system will be needed in order to start the engine	7	engines are typically $150; other significant costs include development of starter system fuel tank, and system hardening	5	higher power per volume than the electric option, but not quite as high as the wankel option	6	some re-design of the engine may be necessary in order to survive high-g's; a starter system would have to be designed	7	best relative fuel efficiency allows this system to meet the loiter time requirements with less fuel, which leads to less total volume needed for the system

Chapter 5 WASP Concepts and Down-Selection

5.1 Development of Three WASP Concepts

The conceptual design phase of the project led to three WASP concepts that were fully investigated and compared with one another in order to choose the single WASP concept that would be produced. The first concept that will be discussed was titled Silent Eyes after the Army's Silent Eyes glider, which is planned to be launched from a 155 mm artillery shell. Like the Army's project, Silent Eyes has no propulsion system, and it will rely on its light weight and high aspect ratio wings to provide long loiter time and range. However, originally, the team attempted to include a propulsion system in this concept, but it was determined that it did not have the required volume to include any of the propulsion system options listed in Chapter 4. The characteristics of the Silent Eyes concept are listed below:

Table 15: Silent Eyes Design Characteristics

Estimated Mass (kg)	Wingspan (cm)	Chord (cm)	Power/Prop System Volume Available (cm^3)
7	160	6	198

Three-dimensional views of the Silent Eyes concept in its four different states during its operation are shown below. State 1 shows the configuration during the launch phase. State 2 shows that the Silent Eyes concept is contained within the five inch shell. It is deployed by being pulled through the back end of the shell by a parachute, which is also used to slow the vehicle down. State 3 is the Silent Eyes concept during wing and tail deployment. All joints for this deployment are simple, scissors-like joints. The wing is actually comprised of two components that are stored on top of each other, and they deploy in the same manner that scissors open. State 4 depicts the system in its final flyer configuration.

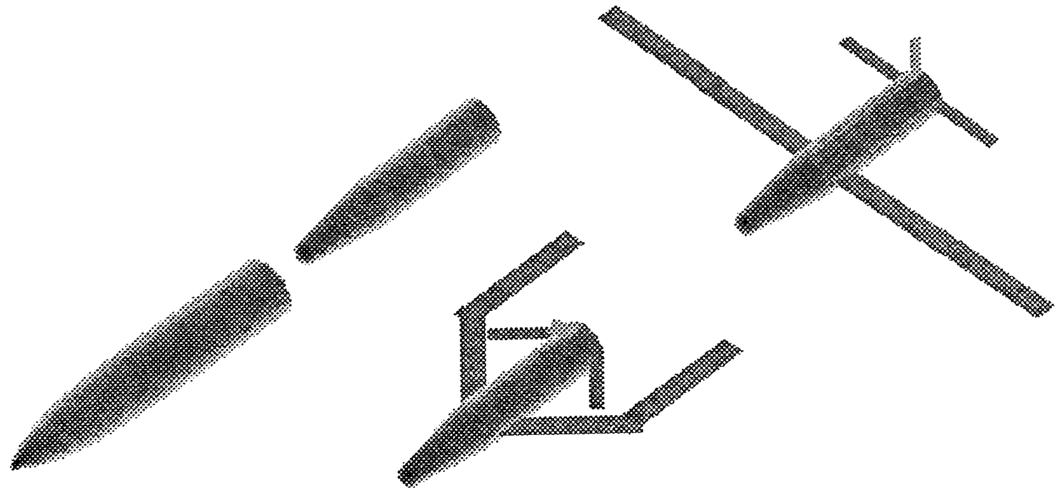


Figure 15: Three-Dimensional Schematics of the Silent Eyes Concept

The second concept that will be discussed was titled Super Shell. Unlike Silent Eyes, this concept had sufficient volume for a propulsion system. Therefore, the two stroke Thunder Tiger option discussed in Sections 4.4 and 4.5 was incorporated into this design. The characteristics of the Super Shell concept are listed below:

Table 16: Super Shell Design Characteristics

Est. Mass (kg)	Inner Wingspan (cm)	Outer Wingspan (cm)	Inner Chord (cm)	Outer Chord (cm)	Power/Prop. System Vol. Avail. (cm^3)
14.5	68.7	50	12	7	560

Three-dimensional views of the Super Shell concept in its three different states during its operation are shown below. State 1 shows the configuration during the launch phase. State 2 shows that the Super Shell concept is one where the actual shell transforms into the flyer. This design requires that a metal unit, surrounding the shell, be placed at the back of the shell that makes contact with the interior of the gun barrel during launch. When changing to the flyer configuration, a parachute is released from the metal unit at the rear of the shell which separates

the unit from the flyer. The parachute also works to slow the flyer down to a speed where the propulsion system can be turned on. State 3 is the Super Shell concept in its flyer configuration. The flyer remains in this configuration until it is commanded to self-destruct.

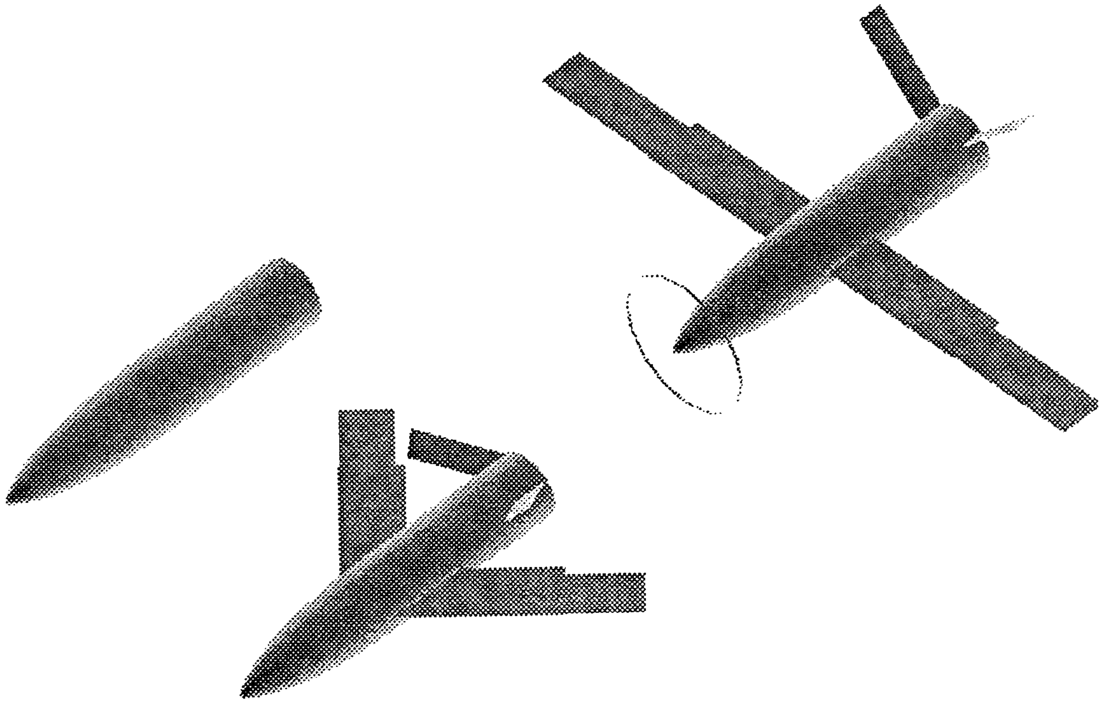


Figure 16: Three-Dimensional Schematics of the Super Shell Concept

The last concept that will be discussed was titled Pinky and the Brain, but it will be referred to as the Twin Shells concept in this paper. This concept involved in interesting design difference when compared to the previous two concepts. The Twin Shells concept was actually two small flyers in one. When in the flyer configuration, each flyer was composed of one-half of the launched shell. For stability, this design had a canard because it did not have enough volume for a tail. Like Super Shell, this concept had sufficient room for a propulsion system, but the only propulsion system that fit into this design was the two stroke Thunder Tiger option discussed in Sections 4.4 and 4.5. Also, only one-half the required fuel volume for a ten minute engine run time was available in this concept. Therefore, the loiter time, range, and surveillance area characteristics for the Twin Shells concept would largely be dependent on the flyers' ability to glide efficiently. The characteristics of the Twin Shells concept are listed below. The estimated mass is the mass for each flyer.

Table 17: Twin Shells Design Characteristics

Est. Mass (kg)	Wingspan (cm)	Wing Chord (cm)	Canard Span (cm)	Canard Chord (cm)	Power/Prop. System Vol. Avail. (cm^3)
4.43	100	4	28	3	396

Three-dimensional views of the Twin Shells concept in its four different states during its operation are shown below. State 1 shows the configuration during the launch phase. Notice that both halves of the shell remain intact. State 2 shows the launched shell after it breaks into its two equal halves prior to deploying wings and canards. Like the Super Shell design, this design requires that a metal unit be placed at the back of the shell that makes contact with the interior of the gun barrel during launch. This metal unit would also be used to help hold the two shell halves together during the launch phase of the mission. State 3 shows the Twin Shells concept transitioning to its flyer configuration. The wing and canard joints are simple, scissors-like joints. State 4 shows both flyers in their final flyer configurations. Unlike the Super Shell concept, the propulsion system for this concept is used to push the aircraft. The flyer remains in this configuration until it is commanded to self-destruct.

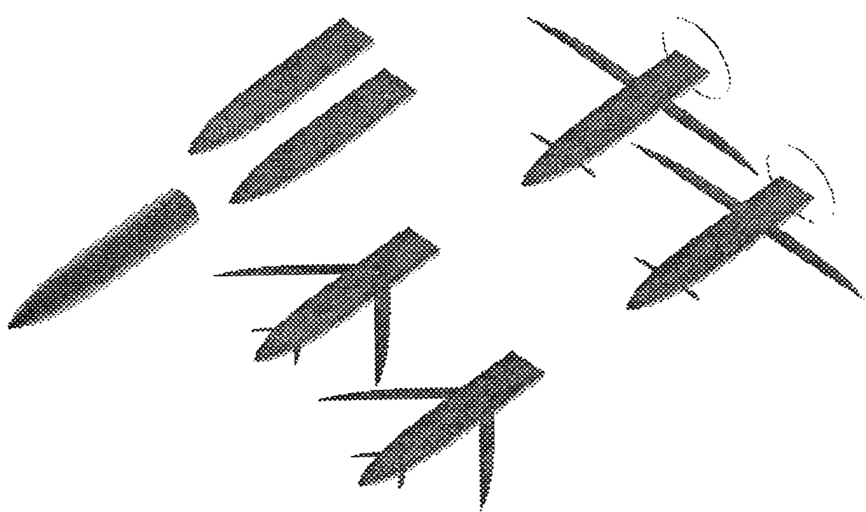


Figure 17: Three-Dimensional Schematics of the Twin Shells Concept

5.2 Propulsion Subsystem Sizing for Three WASP Concepts

For each of the three concepts above, an attempt was made to include a propulsion system in order to increase loiter time, surveillance area, and range for each concept. As discussed earlier for the Silent Eyes concept, there was simply not enough volume within the concept to include even the smallest propulsion option, the Thunder Tiger two stroke engine. Therefore, Silent Eyes had to rely on its efficient glider performance in order to compete with the other two concepts.

For the Twin Shells concept, the Thunder Tiger system was the only propulsion system that could possibly be employed in the concept due to volume constraints. As mentioned previously, each flyer could only carry enough fuel to run the engine for five minutes. This small engine run time raised the question of whether or not the cost of development of a propulsion system for this concept would justify the additional five minutes of loiter time that the flyer would receive. However, probably the largest problem with the fact that the two stroke option was the only propulsion system that could fit into this concept was that if it were determined at a later time that the two stroke option would not be able to survive the high-g environment, then the only fall-back design for the Twin Shell concept would have been to make both of the flyers into gliders, similar to Silent Eyes. Since the two stroke option was the only propulsion system that could fit into the Twin Shells concept, if this system was not feasible, then no propulsion system could be used on this concept.

This problem did not exist for the Super Shell concept. As shown in Table 16, the propulsion and power system volume available for this concept was 560 cm^3. It was estimated that if the Wankel engine were to be run at the same output power level as the Thunder Tiger two stroke engine (0.42 hp), then the fuel requirement for a ten minute run time for the Wankel engine could approximately be cut in half (97 cm^3). The total Wankel propulsion system volume would then be 541 cm^3, which is below the volume this concept has allotted for the propulsion and power systems; however, this total Wankel system volume does not include the batteries required to run the on-board electronics. Therefore, other design changes would need to be incorporated in order to create enough volume to use a Wankel engine for the propulsion system. Some possible design changes include using a smaller propeller since the desired output power is less than the maximum

output 0f 1.27 BHP. Also, the Wankel engine may be able to run without the use of a muffler, which would obviously increase its sound output, but it would help to reduce total system volume. Lastly, one design possibility is to use the starter motor as a generator once the engine is started. By continuing to turn the starter motor while the engine is operating, it may be possible to generate electricity to power some of the components, and therefore, the total battery volume required for the flyer could be decreased.

In summary, there were three significant things learned from this analysis. First, it will be impossible to include a propulsion system in the Silent Eyes concept until significant changes in the sizes of components result in a larger allowable propulsion system volume. Second, if the Twin Shells concept were to be chosen, there would be no fall-back position for the propulsion system. If the two stroke option was determined to be unfeasible, then this concept would not have an on-station propulsion system. Third, the Super Shell concept has the most design flexibility. Through some changes and reconfiguring of components, it may be possible to fit a Wankel propulsion system into this concept. Therefore, if this concept were chosen, it would be possible to develop both a two stroke and a Wankel system concurrently in case one system were deemed unfeasible.

5.3 A Note on the Power Subsystem for WASP Concepts

For the majority of the MIT/Draper Project, the WASP electrical power and power distribution system was neglected. This neglect was, in large part, due to the team's not realizing both the importance of and the difficulty in designing such a system for a high-g environment. Not until the electric propulsion option was being considered did the team begin to address the design of the power system. Due to the team's lack of a background in this area, power system questions were discussed with Carlo Venditti of the Draper Laboratory, who currently works on the power systems for both the Extended Range Guided Munition (ERGM) and the Competent Munitions ATD projects.

During meetings with Mr. Venditti, it was discovered that it may be difficult for WASP to achieve the desired $10,000 cost per shell due to the high cost of high-g tolerant batteries. Currently,

each battery that the Draper Lab tests in its ERGM and ATD projects costs approximately $3,500 [21]. As stated in Section 4.2, Eagle-Picher Industries, Inc. is the largest and most respected of the companies who manufacture these types of batteries, and therefore, the price stated above is Eagle-Picher's price.

Venditti also called the power distribution system for WASP to the team's attention. Until this point, the team had not made an attempt to determine how power would be sent from the battery to the various electrical components. It was found that the power distribution system requires a significant amount of volume, and the shape of this system is not as flexible as might be desired. The high-g DC/DC converters currently in production are approximately 1.5 inches long, 1.5 inches wide, and 0.375 inches high. At least two of these may be needed for WASP, and they are usually placed on the same silicon board, though this is not necessary. Venditti felt that the smallest power distribution board that could be realized for the WASP flyer was approximately 3 inches long, 3 inches wide, and 0.5 inches high [21]. This board cannot be easily reshaped, and it requires a significant portion of the internal volume of the shell. However, before making assumptions about the true size of the power distribution system, it was prudent to determine the actual power requirements for the WASP flyer. Table 18 shows the power requirements for each of the system's components, as well as the total power requirements for the system.

Table 18: WASP Flyer Power Requirements

Component	Number Required	Voltage Required	Current Required	Power Req'd Each Comp.	Total Power Required
Sensor	1	7	200 mA	1.4 W	1.4 W
Receiver	1	17	200 mA	3.5 W	3.5 W
Transmitter	1	17	200 mA	3.5 W	3.5 W
Actuators	2	6	417 mA	2.5 W	5.0 W
Processor Board	1	5	1.73 A	8.65 W	8.65 W
GPS Board	1	5	1.73 A	8.65 W	8.65 W
Accelerometers	3	12 V	64 mA	0.768 W	2.3 W
Gyros	3	12 V	64 mA	0.768 W	2.3 W
		Max Voltage Required	**Max Current Required**		**Total System Power Req'd**
Total System		**17 V**	**1.73 A**		**35.3 W**

The majority of the information on the components listed in Table 18 was given to the team by members of the Draper Laboratory. The components are either in use on the ERGM project, or it is anticipated that they will be used on the ATD project. The battery being used on Draper's ERGM project is the Eagle-Picher Industries, Inc. MAP-9233, which is a primary Lithium Thionyl Chloride Battery with the following characteristics:

Table 19: ERGM Battery Characteristics

Part No.	Weight (kg)	Volume (cm^3)	Height (cm)	Diameter (cm)	Voltage (V)	Capacity (AHrs)
MAP-9233	0.465	102	5.918	5.080	36.5	0.375

An advantage of this battery over other kinds of batteries is that its ability to handle high g-loads has already been tested. It can withstand a shock load due to launch of 15,900 g's and a rotation frequency of up to 450 Hz. During tests, with a 24 V cutoff and a resistance of 104 Ohms, the battery was able to supply 0.25 A of current for 90 minutes [22]. Therefore, it was assumed that if the voltage level of this battery were dropped to match the highest WASP voltage requirement of 17 V, then the current can be increased to the highest WASP requirement of 1.73 A, and the WASP flyer will have sufficient power for its desired operational flight time. It was pointed out that the WASP shell might actually reach 30,000 g's due to its light weight. Currently, there is no battery that has been tested for these high g-loads, and it is suggested by Eagle-Picher that all efforts be made to lower the g-load to levels where the batteries have already been tested. Therefore, weight may need to be added to the shell in order to decrease the g's and enable the power system to survive.

However, there is a significant disadvantage to using this battery in the WASP flyer. The MAP-9233 is a primary battery with a limited shelf life. The longer this battery is stored before it is used, the shorter the operational time for the WASP flyer will be. Therefore, one option that must be investigated for the WASP flyer is the use of a reserve battery. These batteries work on the same principles as the primary Lithium Thionyl Chloride batteries, but like thermal batteries, they have relatively long shelf lives of approximately three to five years while being stored at 20° C [34]. Reserve batteries are activated by addition of the electrolyte, which can be done either manually or automatically through electrical or mechanical means [34]. The Eagle-Picher battery

to be considered for the WASP flyer uses the firing of an internal squib to activate, and it typically requires 0.5 A of current for 50 milliseconds [23]. Another advantage to using a reserve battery is that the storage of lithium batteries is no longer a problem. The reserve batteries can simply be placed in the flyer when the system is manufactured, and there is no need for the user to store batteries or insert the battery before launch. If primary batteries are used, then the military units that use the WASP system would have to have special storage areas for these types of batteries because lithium batteries require "hazardous material storage" [21]. The physical characteristics of the reserve battery to be investigated are shown below.

Table 20: Reserve Battery Characteristics

Part No.	Weight (kg)	Volume (cm^3)	Height (cm)	Diameter (cm)	Voltage (V)	Capacity (AHrs)
GAP-9146	0.350	83.4	5.283	6.350	14.8	1.1

The Eagle-Picher Primary and Reserve Battery Manual also states that this battery is capable of withstanding a shock load due to launch of 18,000 g's, which means that it would most likely not have to be redesigned before being implemented in the WASP system.

Work on the power and power distribution system stopped at this point due to a lack of experience of the team members in this area. If the design progress had progressed in a more correct manner, one team member would have been assigned to the development of the power subsystem when the project was first selected in January of 1997. According to Venditti, power subsystem development for a high-g system can take up to two years, in itself [21]. At the time of completion of this thesis, a power subsystem will need to be fully designed and built within one year. This late start on power subsystem design could lead to later problems, but if design work on this system is started immediately, this system will not be a "show-stopper" in the development of the WASP system due to the Draper Laboratory's expertise in this area..

5.4 Trade Study for Three WASP Concepts

Once the conceptual designs for the three concepts were completed, the team needed to develop criteria to be used for objectively comparing each of the concepts with the other two. Discussions with team members led to the development of the ten criteria and their weightings listed below. It

was felt that these criteria, together, encompassed a complete description of a concept's ability to answer the customer's needs. Therefore, these criteria were sufficient for objectively comparing the three concepts.

1. *Loiter Time*: the amount of time, in seconds, that a concept required to fly from 1000 meters of altitude to ground impact. The 1000 meters of altitude starting point was the result of the analysis in Section 3.1. Longer loiter times were determined to be better than shorter, and therefore, a weighting of 10 was assigned to this criterion.
2. *Inert Mass Fraction*: the ability to carry a large payload, which is sensor and fuel mass. The following formula was used for this calculation:

$$f_{inert} = \frac{M_{total} - M_{payload} - M_{fuel}}{M_{total}} \tag{5.1}$$

   where: M_{total} was the total vehicle mass, $M_{payload}$ was the payload, or sensor mass, and M_{fuel} was the fuel mass for the vehicle. The inert mass fraction was given a weight of -8 because higher inert mass fractions reflected a concept's greater inability to carry a large payload.
3. *Surveillance Area*: the total area in square kilometers that a concept could cover with a 30 degree field-of-view from 1000 meters of altitude to ground impact. Larger areas reflected a concept's higher capability, and therefore, this criterion was given a weight of 8.
4. *System Complexity*: a subjective judgment that measured the relative overall complexity of a concept. High system complexity was undesirable, and therefore, this criterion was given a weighting of -7.
5. *Deployment Scheme Complexity*: a subjective judgment that measured the relative difficulty of the proposed flyer deployment scheme for each concept. Again, high complexity was undesirable, and therefore, this criterion was given a weighting of -7.
6. *Electrical Power Volume Available*: a concept's ability to carry battery power for the on-board electronics. The number presented in the table in the volume available for batteries in cubic centimeters. This value was related to a concept's ability to remain operational for a long period of time. Larger volumes were considered better, and therefore, the criterion was given a weighting of 7.

7. *Lift-to-Drag Ratio*: a simple comparison of the estimated L/D for each concept, and it was given a weighting of 6.
8. *Flyer Range*: the estimated distance in kilometers that a concept would travel from 1000 meters of altitude to ground impact, and it was given a weighting of 5.
9. *Cost*: the estimated mid-range price for a single unit of each concept. High costs were undesirable, and therefore, this criterion was given a weighting of -10.
10. *Component Technology Available*: a relative subjective judgment made for each concept based on the amount of componentry that was currently in existence at the time of this analysis. Higher numbers were given to those concepts that had a greater availability of components. This criterion was given a weighting of 8.

Once the numbers for each of the ten criteria were determined, a selection matrix was developed that contained the ten criteria, their weightings, and the estimated values for each of the three concepts. The next step in the development of the selection matrix was to choose a baseline concept. Scores for the other two concepts would then be related to the baseline concept, with higher scores reflecting better system performance than the baseline, and lower scores reflecting worse performance that the baseline. For the baseline, the Silent Eyes concept was used because of the flyer's simplicity. However, any of the concepts could have been chosen for the baseline.

Next, comparative values for the baseline were calculated by dividing the numerical value for each of the criteria by itself. Therefore, for the baseline, all comparative values were 1. However, comparative values for the other two concepts were calculated by dividing each concept's numerical value for each criteria by the baseline numerical value. For example, the estimated cost for Super Shell was $72,205, and the estimated cost for Silent Eyes was $39,520. The comparative value for cost for Silent Eyes was 1, and the comparative value for cost for Super Shell was 1.827. Weighted scores for each concept were calculated by multiplying the weighting for a criterion by the comparative value. For example, the weighted score for cost for Silent Eyes was -10, and the weighted score for Super Shell was -18.27. The weighted scores for each of the criteria for each concept were then summed to determine a total score for each of the concepts. A relative score was then calculated by dividing all total scores by the total score for the baseline

concept. Table 21, below, which was taken from Bernstein, was the selection matrix that resulted from the MIT/Draper team's research [9].

Table 21: Concept Selection Matrix

Measure	Units	Weighting	Glider Numerical Value	Glider Comparative Score	Glider Weighted Score	Supershell Numerical Value	Supershell Comparative Score	Supershell Weighted Score	Twin Shells Numerical Value	Twin Shells Comparative Score	Twin Shells Weighted Score
Cost	dollars	-10	39520	1	-10	72205	1.83	-18.27	163045	4.13	-41.26
System Complexity	subjective	-10	4	1	-10	7	1.75	-17.50	10	2.50	-25.00
Loiter Time	seconds	10	830	1	10	1358	1.64	16.36	721.5	0.87	8.69
Inert Mass Fraction	-	-8	0.97	1	-8	0.98	1.01	-8.08	0.99	1.02	-8.16
Surveillance Area	square kilometers	8	19.5	1	8	48.2	2.47	19.77	34.8	1.78	14.28
Component Technology Availability	subjective	8	9	1	8	7	0.78	6.22	3	0.33	2.67
Deployment Scheme Complexity	subjective	-7	3	1	-7	5	1.67	-11.67	9	3.00	-21.00
Electrical Power Volume Available	cubic centimeters	7	198	1	7	259	1.31	9.16	144	0.73	5.09
Lift-to-Drag Ratio	-	6	22.5	1	6	19.9	0.88	5.31	19.9	0.88	5.31
Flyer Range	kilometers	5	19.9	1	5	58.1	2.92	14.60	37.7	1.89	9.47
				Total Score	9		***Total Score***	15.90		***Total Score***	-49.91
				Relative Score	1		***Relative Score***	1.77		***Relative Score***	-5.55

Note:
- The Glider variant did *not* have space for a self-destruct mechanism, so such a device was left out.

This omission means that the design does *NOT meet all of the requirements for the system.*

Once the selection matrix was completed, the team was able to make a decision about which concept it would continue to develop. Table 21 displayed the scores for Cost, System Complexity, and Deployment Scheme Complexity for the Twin Shells concept inside of circles because of the significant disadvantages that the Twin Shell concept had in comparison to the baseline concept for these criteria. Together, the scores for these three criteria for the Twin Shells concept, when combined with the scores for the other criteria, resulted in a negative relative score that was 5.55 times the magnitude of the baseline's relative score. The Component Technology Available criterion also played a factor in the calculation of the total score for the Twin Shells because, at the time of this analysis, a small amount of the components that the concept was designed for were actually in existence. Therefore, Table 21 made it obvious that the Twin Shells concept's performance could not compete with the baseline concept. At this point, the team eliminated the Twin Shells concept based on its high system cost, high complexity, and poor component availability, which resulted in overall poor performance for the concept.

Table 21 displayed the scores for Surveillance Area and Range for the Super Shell concept inside of circles because of the significant advantages that the Super Shell concept presented over the Silent Eyes, or baseline, concept for these important criteria. Together, these two improvements over the baseline design helped to give the Super Shell concept a relative score of 1.77 times that of the baseline concept. However, it was not obvious from this result that the Super Shell concept was necessarily a better choice than the baseline Silent Eyes concept. The selection matrix would seem to indicate a relative higher overall performance for the Super Shell concept, however, the Silent Eyes concept had some important advantages of its own, such as relatively low system and deployment scheme complexity. Therefore, some additional information was used in order to choose between these two concepts.

Relative design flexibility for the two concepts was discussed by the team, and it was determined that the Super Shell concept had significantly greater design flexibility than Silent Eyes because the Super Shell concept had a fall-back option where the concept would not carry a propulsion system. If at some point in the design process, it was discovered that the components for Super

Shell could not fit into the space allotted, then the propulsion system could be eliminated in order to create more volume for necessary components.

One of the original requirements for the WASP system was that it had to have a self-destruct capability. The Silent Eyes concept had no volume allotted for this feature, whereas Super Shell did leave sufficient volume for such a device. Therefore, Silent Eyes did not answer all of the original requirements for the system.

Similarities between the Army's gun-launched glider and the team's Silent Eyes concept significantly hurt this concept's chances of being chosen. The purpose of the MIT/Draper Project was not to duplicate another project or compete with a very similar product, but rather to attack a new area of some market, or solve a problem in a new manner. Therefore, choosing to develop the Silent Eyes concept while the Army's glider design was being developed meant that the MIT/Draper team would have been entering the same market as another organization.

The last non-numerical measure of the two systems that was used in the decision process was the amount of "unobtainium" that each concept presented. While both projects were certainly challenging, the level of difficulty associated with the development of Super Shell was much higher than that of Silent Eyes due to its composite construction, on-station propulsion system, and complex deployment scheme. Based on the four non-numerical measures discussed above, it was decided that the Super Shell concept afforded the MIT/Draper team the best opportunity to solve a current national need.

Chapter 6 Propulsion Subsystem Preliminary Design and Test Plan

6.1 Propulsion Subsystem Schematic Block Diagram

This thesis will only cover the preliminary design of the propulsion system for the Super Shell concept. For the preliminary design of the communications system, please reference *Systems Design and Communications Subsystem of an Innovative Projectile* [35]. For the preliminary design of the aerodynamic configuration, please reference *Rapid-Response Surveillance System Design and Aerodynamic Modeling* [36]. For the preliminary design of the composite shell, as well as launch trajectory information, please reference *MIT/Draper Technology Development Partnership Project: Aerodeceleration, Structures, and Systems Design of a High-G, Rapid Response, Deployable, Unmanned Aerial Vehicle* [11].

Preliminary design of the propulsion system began with the development of a schematic block diagram, or SBD, in order to help gain an understanding of the various interfaces that would be necessary between components of the propulsion system. The SBD for the propulsion system is shown below:

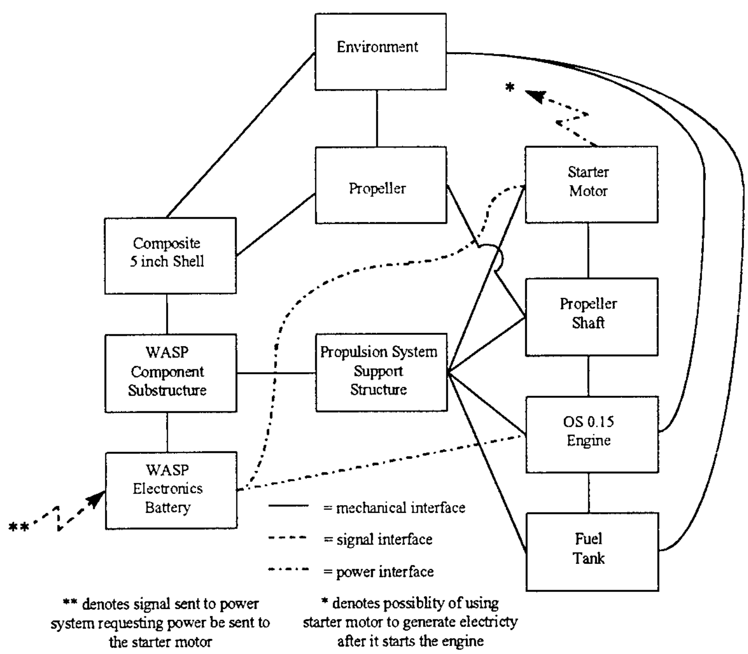


Figure 18: Propulsion System Schematic Block Diagram

The schematic block diagram in Figure 18 displays the engine to be used as an OS Engines 0.15, rather than a Thunder Tiger 0.15. During a discussion with Alex Zander of Alex's R/C Hobbyworks in Watertown, MA, it was found that the OS Engines 0.15 has nearly the exact dimensions of the Thunder Tiger 0.15, and it has the identical power output of 0.42 horsepower [37]. A decision was made to use the OS engine for testing rather than the Thunder Tiger engine because the OS engine is accepted to be the most reliable engine made today for radio-controlled aircraft [37]. Its price is generally $5 to $10 more expensive, which reflects its higher quality. From this point on, information given for the Thunder Tiger engine will be accepted as equivalent to the OS engine.

The SBD above shows the various mechanical, power, and signal interfaces that exist between all components of the propulsion subsystem. The only signal interface that exists in this system is one that commands power to be sent to the starter motor and glow plug. No signals are required beyond this point in the sequence. There are three possible power interfaces. The two mandatory power interfaces are between the WASP battery and the starter motor and between the WASP battery and the glow plug. The third possible interface depends on testing during the summer of 1997. As was stated in Section 5.2, it may be possible to leave the starter motor coupled to the engine after the engine is started. By turning the starter motor from the engine's power, it may be possible to use the starter motor as a generator for electricity to run the WASP electronics. Testing during the summer of 1997 will reveal how much power is drained from the engine in order to run the motor, and what the effects this power decrease will have on loiter time and ability to remain at a constant altitude. The option to generate electricity from the motor seems to make the Wankel engine more attractive because of this engine's oversized power output, but testing of the OS 0.15 will give better insight.

6.2 Propulsion Subsystem Preliminary Design

In this section, a possible subsystem design is presented, including a possible remote starting method and a possible propeller design. However, this design is in no way final. Significant concerns about the propeller and the remote starter system, in particular, still exist. These concerns are discussed, but a detailed design for the propulsion subsystem, as a whole, is not

given due to time constraints on the project. The detailed design for this subsystem will begin during the summer of 1997.

The preliminary aerodynamic design for the WASP flyer reveals that the flyer will need to fly at a speed of nearly 100 miles per hour in order to remain stable [36]. Therefore, the question to be asked is whether or not the OS 0.15 can handle velocities this high. The OS 0.15 is designed to use a 8-6 propeller, meaning a two-blade, 8 inch diameter propeller that it is designed to advance 6 inches forward for every revolution of the propeller. However, as *All About Engines* states, the true advance ratio of propellers for radio-controlled aircraft almost never matches its stated advance ratio; rather, the advance ratio is almost always below the stated ratio [30]. The plot below shows the speeds that the OS 0.15 can achieve at three different RPM settings for a range of advance ratios. The OS 0.15 experiences its maximum power output at 17000 RPM, and therefore, if possible, the team would like to see the flyer achieve the desired 100 mph at this RPM.

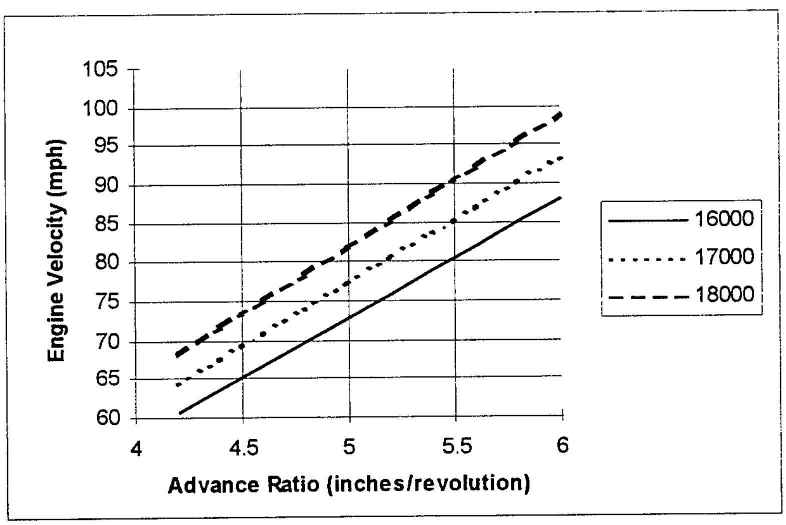


Figure 19: Engine Velocity as a Function of Advance Ratio

As the plot shows, there is no RPM setting or advance ratio where the OS 0.15 will achieve the desired 100 mph. However, this finding is not a "show-stopper" by any means. The output power of the OS 0.15 is estimated to be just below the required power for straight and level flight for the WASP flyer, which is approximately 0.5 hp. This lower power means that the flyer will

actually be decreasing in altitude while the engine is running, and therefore, its acceleration due to gravity will add some velocity to the flyer. According to Figure 19, at 17000 RPM, the flyer will only need an additional 5 to 10 mph of speed in order to remain stable. By using gravity for this additional 5 to 10 mph, the engine will supply the rest of the required power, and the flyer will remain stable.

It is also necessary to keep in mind that this engine is said to work best with an 8-6 propeller because this is the mass-manufactured propeller that best fits this engine. This propeller is claimed to have an efficiency of between 80% and 85%, which makes the efficiency assumptions used earlier valid. However, as the system design progresses, it may be found that a more nearly optimal propeller could be produced by the team.

The propulsion system preliminary design continued with a determination of the exact dimensions of the two stroke Thunder Tiger engine. A facsimile from Thunder Tiger USA listed the dimensions as shown in the figure below [33]. The length of the engine, 2.25 inches, is not shown.

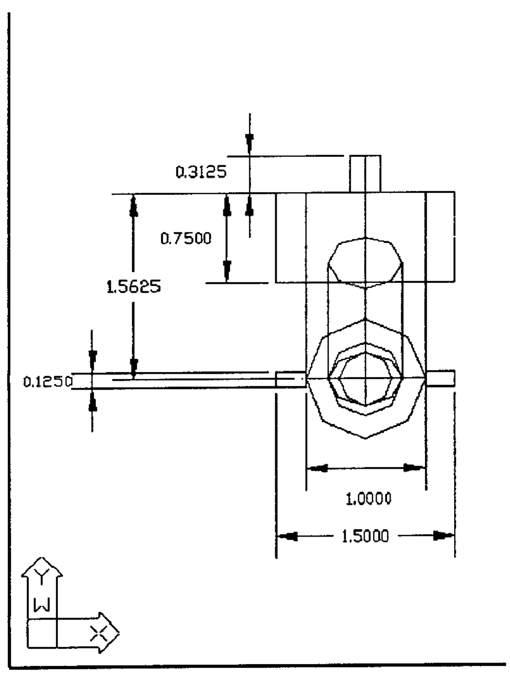


Figure 20: Thunder Tiger Engine Dimensions

Using these dimensions, the engine, starter motor, and propeller shaft with propeller were drawn using AutoCAD. These components, shown as a system, are displayed below.

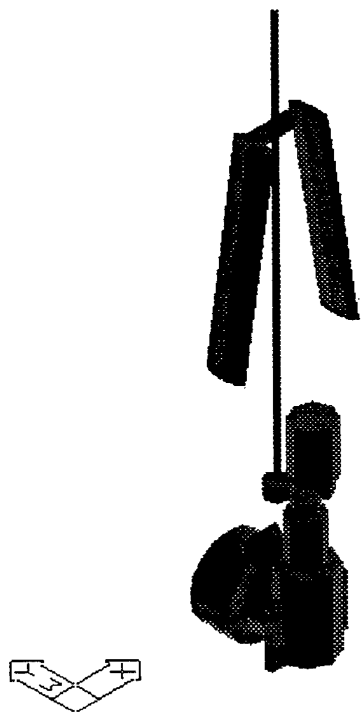


Figure 21: Thunder Tiger Engine, Starter Motor, Propeller Shaft, and Propeller

Each blade of the propeller was drawn as an elliptical cylinder with a thickness of 0.25 inches in one axis, a thickness of 0.75 inches in the second axis, and a height of 3.7 inches. The relatively small diameter of the 5 inch shell does not afford the opportunity to use a solid propeller. Therefore, the propeller will need to be deployed, which is why the propeller is drawn as two blades, each connected to a single bar that connects them to the propeller shaft. Propellers such as these are most often used with electric motors for radio-controlled aircraft, and there are no known deployable propellers used on two stroke engines. The relatively low RPM's of electric motors, approximately 6500 RPM for electric motors versus 17000 RPM for two stroke engines, is what allows these deployable propellers to be used [37]. The joints between the connecting bar the propellers is a weak joint that would be broken if used on two stroke engines [37]. Therefore, the deployable propeller for the two stroke engine is something that will need to be built by the MIT/Draper Project team. Note that the propeller blades are drawn at angles to the propeller

shaft. The current design being considered for the propulsion system places the propeller blades on the outside of the shell, but embedded into its surface so that the exterior surface of the shell is still smooth. This design complicates the design of the shell somewhat, but it is the only possible method for propeller placement that can be thought of at this time. The drawing below is a three-dimensional view of the propulsion system inside of the cone of the 5 inch shell. This picture shows the propeller blades flush against the sides of the shell.

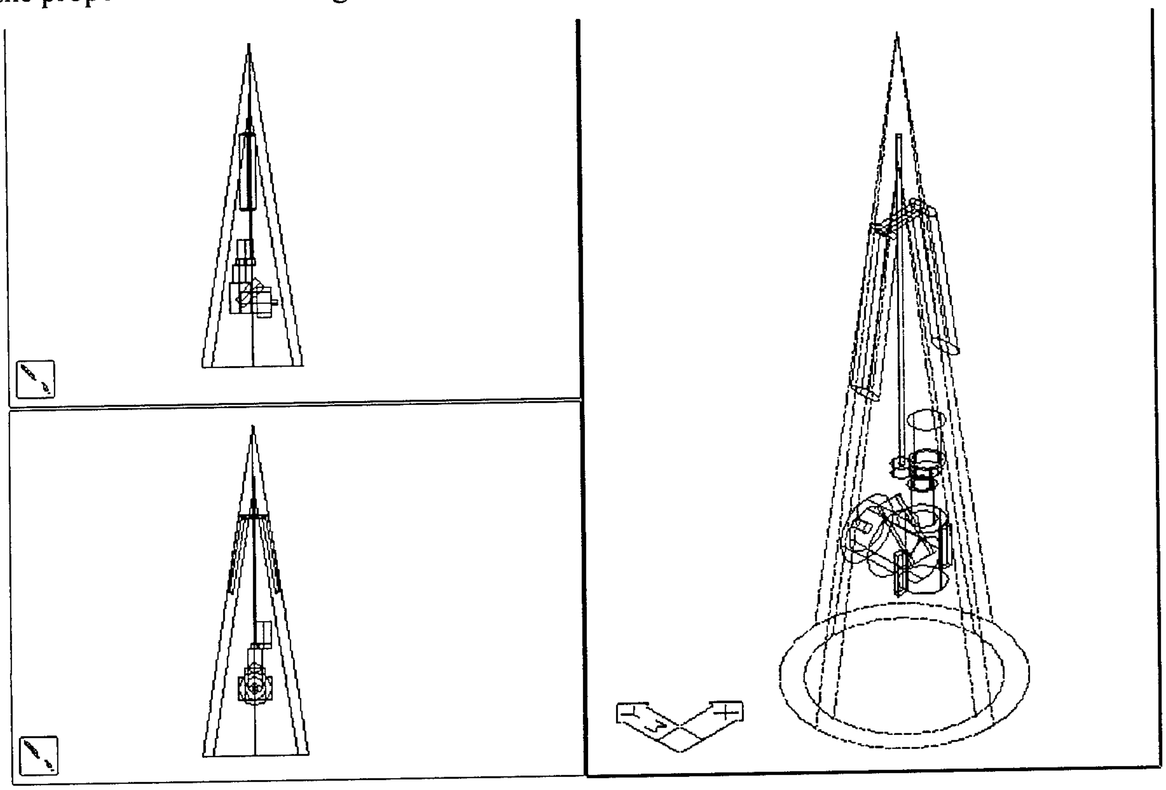


Figure 22: Propulsion System Placement Inside of the 5 Inch Shell

Figure 22 depicts the cone of the shell as having straight sides, which is not the true case. In reality, the shell cone has curved sides with a 30 inch radius, which slightly increases the internal volume available. Therefore, the cone size shown in Figure 22 is a conservative estimate.

Due to the fact that the blades do not come together at the point of the shell, a nose cone will have to be manufactured as well. The propeller shaft is drawn through the propeller blade connecting rod in Figure 21 for this reason. It is anticipated that the nose cone will screw onto the propeller shaft. The starter motor drawn in Figures 21 and 22 was only an estimate based on

the size used in Section 4.4. The actual size and design of this component may change significantly due to the fact that such starter motors are not currently in existence, and the actual starter motor system will have to be designed by the MIT/Draper team. However, it is not anticipated that the lack of development of remote starter systems will make the development of this part of the system a "show-stopper." As was discussed in Section 4.2, it is anticipated that electric motors will be able to survive high-g's, and the starter motor is simply an electric motor connected to the engine. At this point, research on the propulsion system for the 1996-1997 academic year stopped. Anticipated future research can best be explained through the form of the test plan that has been developed, which is discussed in the next section.

6.3 Propulsion Subsystem Test Plan

During a meeting with the MIT/Draper Project team, a question was raised as to whether or not radio-controlled model engines such as the OS 0.15 can even survive the accidents that occur during radio-controlled flight. The short answer to this question is that many times these engines do break to the point where repair is necessary before the engines can be used again. However, this fact should not discourage the project team. There are actually two more important questions that need to be answered through research. First, if the engine is properly supported, will it be able to survive the launch environment? Second, if the engine cannot survive the launch environment, how significant are the design changes that are required in order to make the engine survive the launch environment? During the summer of 1997, the project team hopes to determine some answers to these questions.

The test plan for the propulsion system was based on what the team defined as the final product that it would supply to the Draper Laboratory. It was determined that the remaining one year period would be insufficient for the team to fully develop the entire WASP system. Therefore, the final test vehicle for the MIT/Draper Project was broken into two vehicles: a High-G Test Vehicle (HGTV) and an Air Drop Test Flyer (ADTF).

The purpose of the HGTV is to validate the structural design of the WASP system. As a result, most internal components will not be tested in this test vehicle. Rather, placebos of identical size

and weight will be placed into the correct places for each subsystem. Therefore, though the propulsion system will be designed both so that it will fit into the shell and withstand high-g's, it will not be included in this testing. Instead, the propulsion system is planned for its own series of high-g tests. Originally, the team planned to test the propulsion system in the large Draper Laboratory centrifuge. However, the team has learned that even the largest centrifuge that Draper offers will not be large enough to contain the OS 0.15 engine. It may be possible, however, to test the starter motor in this centrifuge. For the g-testing of the engine, there are two main options. First, the engine may be dropped in a test cell from a high altitude, such as the roof of a four or five story building. Currently, this type of testing is just an idea, and no more thought has been given to it. The second possibility for g-testing of the engine is to launch it inside the rail gun at the Picatinny Arsenal. This testing would best approximate the actual launch environment, but it would also be quite expensive. Hopefully, this testing will be performed early in the summer of 1997 so that the survivability and necessary re-designs, if any, for the OS 0.15 can be determined. If the OS 0.15 is determined to be too risky for the WASP flyer, then the Wankel engine will be researched.

The purpose of the ADTV is to validate the WASP flyer's aerodynamic design. The ADTV will be designed so that it closely resembles the final WASP flyer design. The components for the ADTV will not necessarily be g-hardened. Instead, every effort will be made to demonstrate the functionality of the operational system, and off-the-shelf components will be included, if need be. The propulsion system on the ADTV will demonstrate a remote-start capability, propeller deployment, and a full ten-minute run time assuming that the flyer will have sufficient room for fuel. Therefore, for this vehicle, integrated propulsion system design and tests will mainly be focused on demonstration of the estimated performance, rather than high-g tolerance.

The requirements for the HGTV and ADTV drove the projected test plan for the summer of 1997. At the time of this writing, a complete engine system had been ordered, including an engine, propeller, fuel, tachometer, and test stand. During the month of June, table top performance tests for the OS 0.15 will be conducted. These tests will include running the engine at a variety of throttle settings in order to determine the engine's fuel consumption over a range of

settings. The throttle will then be adjusted to find the maximum horsepower point, where the throttle will be fixed.

Design work on the remote starter system will also begin during the month of June. Currently, there is only one known remote starter system that exists for radio-controlled aircraft, called the FEMA On-Board Starter System. This system is only produced for engines of 0.40 cubic inches and larger, which means that it will provide the 0.15 engine with greater starting torque than is needed. Some concern exists that this starter may over-torque a small 0.15 engine, but a conversation with Steve Fuqua of MNC Hobbies revealed that trying to start the 0.15 engine with the FEMA system should not be a problem. Therefore, some design will be done during the month of June to connect the FEMA system with the OS 0.15, and the ability to start the engine remotely will be tested. An interesting design feature that the FEMA system employs is a one-way, free-wheeling clutch, which basically works like a one-way bearing. This feature allows the starter to uncouple from the engine once the starting is complete. If it is determined that running the starter motor as a generator requires too much power from the engine, then the clutch design would be a nice feature to employ in the WASP flyer.

It is anticipated that both the survivability of the OS 0.15 in the high-g environment and the power required to generate electricity from the starter motor will be determined by the middle of July. At this point, a decision will be made to continue with the design using the OS 0.15 or to change to the Wankel engine because of its higher power output and anticipated ability to better withstand high-g's.

From the middle of July continuing through the end of the summer of 1997, approximately 18 August, the detailed design of the propulsion system will be conducted. This process will include integration of all components, as well as the development of the deployment scheme for the propeller. At this time, it is anticipated that each of the propeller blades will be held in place with a "holding clip" that is connected to the parachute decelerator system. When the parachute is released from the rear of the shell, its drag force will be great enough to pull the holding clips

toward the rear of the shell to the point where the spring-loaded propeller blades can deploy. At this point, the engine will be ready to start.

From 18 August and continuing on for the rest of the project, the propulsion system design will lie in hands other than the author's. Currently, the propulsion system team replacement is not known, but it is anticipated that the replacement will be found early in the summer of 1997.

Chapter 7 Conclusions and Recommendations

7.1 Conclusions Based on First Semester Research

Due to the ambitious nature of the MIT / Draper Project, with a plan to develop and demonstrate the chosen project within a two year time period, there was a need for this team to integrate the work of many different organizations, rather than design a completely new system, in order to successfully complete the project. Therefore, the information gained through the team's initial semester of research was extremely helpful and important to the success of the project.

First, the MIT / Draper team students learned about specific projects that elements of the entire MIT / Draper / Lincoln team were working on. The student team learned about the strengths of each organization, and it also learned somewhat about the direction each team "element" was heading with its research. By doing this analysis, not only did the team ensure that the selected MIT / Draper project would not be a "reinventing" of a project that has already been done by either Draper, MIT, or Lincoln Lab, but the groundwork was laid for determining whether or not the team would be able to complete the selected project within a two-year timeline.

The second benefit of doing this initial research may be the most valuable part. By creating the library in Appendix A, not only did the team learn what technologies various organizations believe are important to their own future, as well as the nation's future, but the team also learned about specific research projects that were currently being conducted at these organizations. Therefore, this research actually worked as an initial market assessment for various concepts on which the team might consider working. When developing possible opportunities for the team, this initial information helped the team decide whether or not a project was worth pursuing, based on the amount of work that had been done, or was currently being done, in that particular field.

When the team went through the process of gathering information about national needs and acquiring the library of documents, it became clear that the process is not commonly pursued in the early stages of product development. This discovery was something that was alluded to in the book *Competing for the Future* [2] as a problem with the way in which current businesses plan

for the future. It is research and analysis like the MIT / Draper project team performed initially that leads to effective strategic plans for businesses. By learning about national needs and opportunity areas, as well as current research focal points, businesses can more effectively analyze their own strengths and weaknesses, and ultimately determine where they will be the most effective. It is research such as this that will enable businesses to stay atop their fields for years to come, and therefore, this type of analysis should be done by every competing organization.

There were also lessons to be learned during the analysis of each of the possible opportunity areas. As the team investigated the Advanced Aircraft Navigation opportunity area, it was found that the team may have lost sight of its goals of looking both forward and outward. Due to the team's lack of a background in air traffic control, field trips were made to talk with air traffic controllers and other people who were researching the air traffic problem. During these discussions, the importance of talking with the actual product users was realized. Until this point, most of the actual users of the team's concepts had not been contacted at all. Though the project was looking forward in time by trying to create a new system for the future, it had failed to look outside of itself for help in this process. It turns out that some of the most valuable information about the team's concepts came from contact with possible users of the concepts. Therefore, it is extremely important for organizations who undergo any type of similar analysis to have substantial communication with potential users of the product. This communication ensures that the user gets a product that is needed and desired.

There were even lessons to be learned from the project that the Draper Laboratory selected for the team. Initially, the team was disappointed with Draper's selection to continue research on the Sensor-Equipped Projectile. The team's voting had resulted in the Solar Sail being the team's first choice by a large margin, but in hindsight, the team should not have been disappointed with this decision for two reasons. First, after the presentation of the market assessment, it was realized that the benefit that each concept presented to the Draper Laboratory was one of the most important selection criteria. One of the disadvantages of the Solar Sail was that it did not clearly state the advantage that it presented for the Draper Laboratory. In hindsight, when research such as this is done for any organization, the benefit for the organization that "pays the

bills" must be clearly stated. If a convincing argument for the benefits of the Solar Sail could have been clearly communicated to the Draper Laboratory, then the decision may have been different.

Over the course of the market assessment process, one of the criteria on which the concepts were judged was "student fun factor." This criterion was basically a judgment by the team of whether or not work on a particular concept would be fun for the team. Looking back on the final team voting on the concepts, it appears that the team may have regarded this criterion too highly. Members of the team greatly enjoyed the Solar Sail concept because it was the chance for college students to put something into space that everyone would hear about. However, one giant criterion was overlooked somewhat in choosing the Solar Sail. Matching a project's requirements with the facility capabilities was extremely important. It turns out, though, that the Draper Laboratory, Lincoln Laboratory, and MIT really have limited experience in the area of small satellites and the technology associated with solar sails. Rather, in order for this project to have been a success, a partnership or alliance with some other company would have been necessary.

On the other hand, the Sensor-Equipped Projectile fit the Draper, Lincoln, and MIT capabilities extremely well. Based on the research being done in the micro-mechanical division of the Draper Laboratory, as well as the lab's high-g projects, such as ERGM, the Sensor-Equipped Projectile was a logical choice. The author believes that if there were a more objective vote made, then the Sensor-Equipped Projectile would have been the team's first choice. Instead, personal feelings about the Solar Sail led to its being the first choice, which also led to the team's initial disappointment in Draper's decision. However, the Sensor-Equipped Projectile has turned out to be a dynamic and exciting project for the team.

One possibility for limiting these biases when making this type of decision is to rotate the team members for each concept. By allowing each team member to do some work on each concept, it keeps members from becoming attached to one concept because of their work on that particular concept. If a person works on all concepts, then it is not as easy to become attached to one concept. Another benefit of rotating the teams is that each person becomes more familiar with each of the concepts, and they do not have to simply accept what others say as the truth.

7.2 Conclusions Based on Second Semester Research

The second semester of the MIT/Draper Project followed more along that lines of a typical design project than the first semester. Various concepts were explored and compared in detail, and an educated decision was made to continue development of the Super Shell concept. Preliminary design then began. However, though this portion of the project followed a more typical process for a design project, there were still lessons to be learned.

First, the importance of a project manager was realized. Once the project team was split into smaller teams of students each working on a specific subsystem, it was difficult for each team member to keep track of the progress being made on the other subsystems. Therefore, it was an absolute necessity for there to be at least one person who could focus on just the big picture for the project.

However, as the project progresses, it may be necessary to reorganize somewhat. As the project progresses toward testing of both the subsystems and the integrated flyer, the author envisions a much more significant portion of the project manager's time being devoted to setting up testing dates and trips to testing facilities, as well as possibly marketing the concept. Less of the project manager's team may be devoted to the integration of the vehicle.

During the second semester of work, Hallam did preliminary work on the integration of the subsystems by developing a series of Design Structure Matrices which help the team track interfaces between various subsystems. However, though it is extremely important for each of the subsystem teams to keep in mind all of the interfaces with other subsystems, it is not reasonable to assume that the entire system will work if each of the subsystems considers only its own interfaces. For this reason, it seems necessary for the team to appoint a person who would be in charge of all interfaces until the project is completed. This person can keep the whole system picture in mind and ensure that each subsystem team keeps the entire system in mind as well.

There were also many lessons to be learned about the preliminary design process, due to the dividing of the team into smaller subsystem teams. A significant amount of concurrent

engineering took place in this project. Concurrent engineering means that each of the subsystems had a preliminary design performed while the same was being done for other subsystems. This type of engineering is beneficial in that it can save time because analyses are being performed for each subsystem at the same time. However, one major problem can result from this type of engineering. When each subsystem team performed its own analysis, each team also used its own assumptions in many cases. This difference can lead to problems between closely-tied systems, such as the aerodynamic configuration and the propulsion subsystem. If the same lift and drag coefficients, size, and weight are not used by both teams, then their analyses do not coincide, and estimated system performance may be completely incorrect. Therefore, the author feels that it is extremely important during this portion of a project to have one person who is dedicated to keeping track of consistency in assumptions between the various subsystems. Investing this time early in the project eliminates the team having to resolve inconsistencies at a later time.

At the time of this writing, a solid groundwork has been laid for the future of the WASP system. However, the most difficult portion of the project still lies ahead, with one year to the date of completion. The author feels that this ambitious goal leads to the requirement for a larger team of dedicated students. For the 1996-1997 school year, seven graduate students and three UROP students were dedicated to the project, but the UROP students were not able to contribute a substantial amount of time over the second semester of this project because of their already busy schedules. Their work was very important to the progress made by the MIT/Draper team; however, as detailed design and testing of subsystems begins, it may be necessary to compile a team of ten or more graduate students whose theses are related to this project. Therefore, the school is ensuring itself a substantial amount of work on the project from ten or more people.

As for the propulsion subsystem, it is recommended that contact be kept with Alex Zander of Alex's R/C Hobbyworks as long as radio-controlled-type engines are kept as an option. Zander is an experienced radio-controlled aircraft flyer, and he has done a substantial amount of work with the Draper Laboratory on its autonomous helicopter project. Though Zander has no background in the area of g-tolerance, it may be valuable for the team to include him in the design process because of his familiarity with systems of this scale.

As for the focus of the development of the propulsion subsystem, it was stated that performance tests will be done on the OS 0.15 engine, but it is recommended that the main thrust of the research be done on the survivability of the engine in the high-g environment. Realistically, it is this research that will determine whether or not a particular option is feasible for the flyer. If possible, a determination on the survivability of the 0.15 engine should be made as soon as possible so that a decision can be made as to whether or not to research the Wankel engine. By making this decision at an early point, more time will be left for the actual system design. The entire system was not considered to be the highest priority at this point because the survivability of individual components is still in question. The entire system will become a priority once the survivability of the components is determined.

The author feels that that the outlook for this project is very encouraging. Many people at MIT, the Draper Laboratory, Dahlgren, or the Picatinny Arsenal are excited about the development of WASP-type systems. With the right amount of support from the Draper Laboratory and MIT faculty, this project can be a great success in its goal to determine a new, forward-looking system, and design and build that system in a two-year time period.

References

[1] Boppe, C, and J. Deyst, "MIT/Draper Technology Development Partnership Project," Massachusetts Institute of Technology, Cambridge, MA, 6/18/96.

[2] Hamel, G, and C.K. Prahalad, *Competing for the Future*, Harvard Business School, Boston, MA, 1994.

[3] MIT / Draper Technology Development Partnership Project Student Team, *Priorities & Opportunities Document*, Massachusetts Institute of Technology, Cambridge, MA, 23 October, 1996.

[4] White House, *National Critical Technologies List*, Washington, DC, March, 1995.

[5] Pugh, S., *Total Design: Integrated Methods for Successful Product Engineering*, Addison-Wesley, New York, 1991.

[6] MIT / Draper Technology Development Partnership Project Student Team, *Market Assessment Document*, Massachusetts Institute of Technology, Cambridge, MA, January, 1997.

[7] *Low-cost Instrumented Surveillance Projectile (LISP) System Requirements*, Draper Laboratory and Massachusetts Institute of Technology, Cambridge, MA, 2 January, 1997.

[8] Boppe, C., "Requirements Priorities / Traceability: QFD-I," Class Lecture Notes, Course 16.870, Massachusetts Institute of Technology, Cambridge, MA, Fall, 1996.

[9] Bernstein, Joshua, *System Design for a Rapid Response Autonomous Aerial Surveillance Vehicle*, Massachusetts Institute of Technology, Cambridge, MA, May, 1997.

[10] Grady, J.O., *Systems Integration*, CRC Press, Florida, USA, 1994.

[11] Hallam, Cory, *MIT/Draper Technology Development Partnership project: Aerodeceleration, Structures, and Systems Design of a High-G, Rapid Response, Deployable Unmanned Aerial Vehicle*, Massachusetts Institute of Technology, Cambridge, MA, May, 1997.

[12] Coughlin, Tom, Lecture on the NEAR Spacecraft, Massachusetts Institute of Technology, Cambridge, MA, 14 November, 1996.

[13] Sturz, Richard A., Facsimile to Charlie Boppe, 3 January, 1997, Xybion Electronic Systems, San Diego, CA

[14] Larson, Wiley J. and James R. Wertz, *Space Mission Analysis and Design*, Microcosm, Inc., Torrance, California, 1992.

[15] Stinton, Darrol, *The Design of the Aeroplane*, BSP Professional Books, Oxford, 1983.

[16] Anderson, John D. Jr., *Introduction to Flight*, McGraw-Hill, New York, 1989.

[17] Henry, Gary N, Ronald W. Humble, and Wiley J. Larson, *Space Propulsion Analysis and Design*, McGraw-Hill, New York, 1995.

[18] Kress, Bob, Personal interview, 6 February, 1997.

[19] Polumbo, Dave, Personal interview, 7 February, 1997.

[20] Aveox Home Page: www.aveox.com, 7 February, 1997.

[21] Venditti, Carlo, Personal interview, 13 March, 1997.

[22] Eagle-Picher Industries, Inc., *Primary & Reserve Lithium Batteries Manual*, Lithium Batteries Group, Joplin, MO, 1997.

[23] Eagle-Picher Industries, Inc., *Thermal Batteries Manual*, Thermal Batteries Group, Joplin, MO, 1997.

[24] Noviln, Ron, Personal interview, 9 April, 1997.

[25] Norton, Scott, "Naval Surface Fire Support Advanced Technologies," *Surface Warfare*, May/June, 1996.

[26] OS Engines 30 Wankel Page: www.hobbies.net/os/engines/osmg1400.html, 31 January, 1997.

[27] Graupner/OS Model Engine Information Page: www.monito.com/wankel/graupner.html, 4 February, 1997.

[28] RCE Theory and Design Page: www.monito.com/wankel1/rce.html, 4 February, 1997.

[28] Lipeless, Jay, Letter to Ted Conklin, 18 March, 1997, Massachusetts Institute of Technology, Cambridge, MA.

[30] Higley, Harry, *All About Engines*, Harry B. Higley & Sons, Inc., Glenwood, IL, 1992.

[31] Linsalato, Randy, Letter to Ted Conklin, 12 March, 1997, Mecoa Hobbies, San Marino, CA.

[32] MNC Hobbies, Letter to Ted Conklin, 6 March, 1997, Kansas City, MO.

[33] Thunder Tiger USA, Facsimile to Ted Conklin, 24 April, 1997, Dallas, TX.

[34] Crompton, T.R., *Battery Reference Book*, Society of Automotive Engineers, Inc., Warrendale, PA, 1996.

[35] Burba, Matthew, *Systems Design and Communications Subsystem of an Innovative Projectile*, Massachusetts Institute of Technology, Cambridge, MA, May, 1997.

[36] Iranzo-Greus, David, *Rapid Response Surveillance System Design and Aerodynamic Modeling*, Massachusetts Institute of Technology, Cambridge, MA, May, 1997.

[37] Zander, Alex, Personal interview, 1 May, 1997.

Appendix A: National Technological Needs Source Documents and Contact List

Source Documents

U.S. Government Departments

The White House

National Critical technologies Report, March 1995
Joint Aeronautical Commander's Group, S&T Roadmap, March 1996

Defense (DOD)

Air Force

New World Vistas, Air and Space Power for the 21st Century

Navy

Vision for the Navy's Future
From the Sea, Preparing the Naval Service for the 21st Century

U.S. Government Independent Agencies

NASA

Achieving Aeronautics Leadership, Aeronautics Strategic Plan, 1995-2000
NASA Strategic Plan, February 1996
NASA Lewis Strategic Plan,
Report on the Goddard Space Flight Center, Strategic Plan
Goddard Space Flight Center, Strategic Plan
Report of the Advisory Committee on the Future of the U.S. Space Program, 1990
NASA Strategic Plan, May 1994

Environmental Protection Agency (EPA)

Strategic Plan for the Office of Research and Development, May 1996

Federal Aviation Administration

Aviation System Capital Investment Plan, January 1996
FAA Plan for Research, Engineering, and Development, December 1995
Report of the Challenge 2000, 6th March 1996
Airworthiness Assurance R&D Branch, 1995 Research Accomplishments

Assorted Councils

Aerospace Industries Association

National Center for Advanced Technologies, February 1992

National Science and Technology Council

Goals for National Partnership in Aeronautics Research and Technology, August 1995
Committee on Transportation R&D, Strategic Planning Document, 1995
Committee on Fundamental Science, Strategic Planning Document, 1995
Committee on Civilian Industrial Technology, Strategic Planning Document, 1995
Committee on International Science, Eng. & Tech., Strategic Planning Document, 1995

Industry and Programs

OSD/DARO and ARPA

DARPA - Description of Offices and Organization
HAE UAV, Program Solicitation, July 1, 1994
Tactical UAV, Solicitation
Tier II+ UAV System
HAE UAV Program Summary, July 1995
UAV System, Executive Briefing, 12 October 1995
UAV, Annual Report, August 1995
ARPA Tech '96, Systems and Technology Symposium, 22-24 May
The Integrated Airborne Reconnaissance Strategy, Executive Summary

LOCKHEED MARTIN

1995 Annual Report
LMAS Advanced Concepts

BOEING

Industry Customer Needs Comparison, The next Generation Vehicles and Vehicle Systems

Local Institutions

Draper

Guidance Technology Center, Report for the period January - June 1995
1995 Annual Report
Corporate Tech Expo, November 9, 1995
Annual Meeting of the Corporation - 1995, President's Report

Red Team Review of the Draper Small Autonomous Aerial Vehicle (DSAAV)
IR&D List and Summaries

Lincoln

Journals - Summary of Activities
Micro-UAV, Presentation to the 23rd Annual AUVSI Symposium

MIT

Aeronautical & Astronautical Engineering Department

Mechanical Engineering Department

Suggested Research and Thesis Topics, 1995-1996

Material Science and Engineering Department

Current Research Activities
Undergraduate/Grad Study and Research in Materials Science and Engineering

Computer Science and Electrical Engineering Department

Research and Graduate Study
List of Faculty and research interests
Microsystems Technology Laboratory, Annual Report May 1994, May1996
Laboratory for Computer Science Progress Report, July 1994 - June 1995
Laboratory for Computer Science - Research Activities

Ocean Engineering Department

Research, 100th Anniversary Issue
Student Handbook, 1995-1996

Individuals Contacted

Jesse W. McCurdy, Jr. - Technical Director
Ross Perkins
Naval Air Systems Command - Systems Engineering Division

John Ventura - Public Affairs
John Alleva
Department of Energy

Peter Hughes
ESC / XRR

Lt. Rick St. Pierre
HSC / XRI

Greg Colocotronis - Comptroller
Col. Doug Carlson - Deputy Director (HAE UAV Program)
Paul Kozemchak - Strategy and Planning
DARPA

Bob Davis - Vice President, Engineering and Technology
Robert Spitzer - Vice President, Technology - Boeing Commercial Airplane Group
Boeing

Dr. Peter Preusse
Dr. Puzak
Environmental Protection Agency

Matthew Lazarewicz
GE

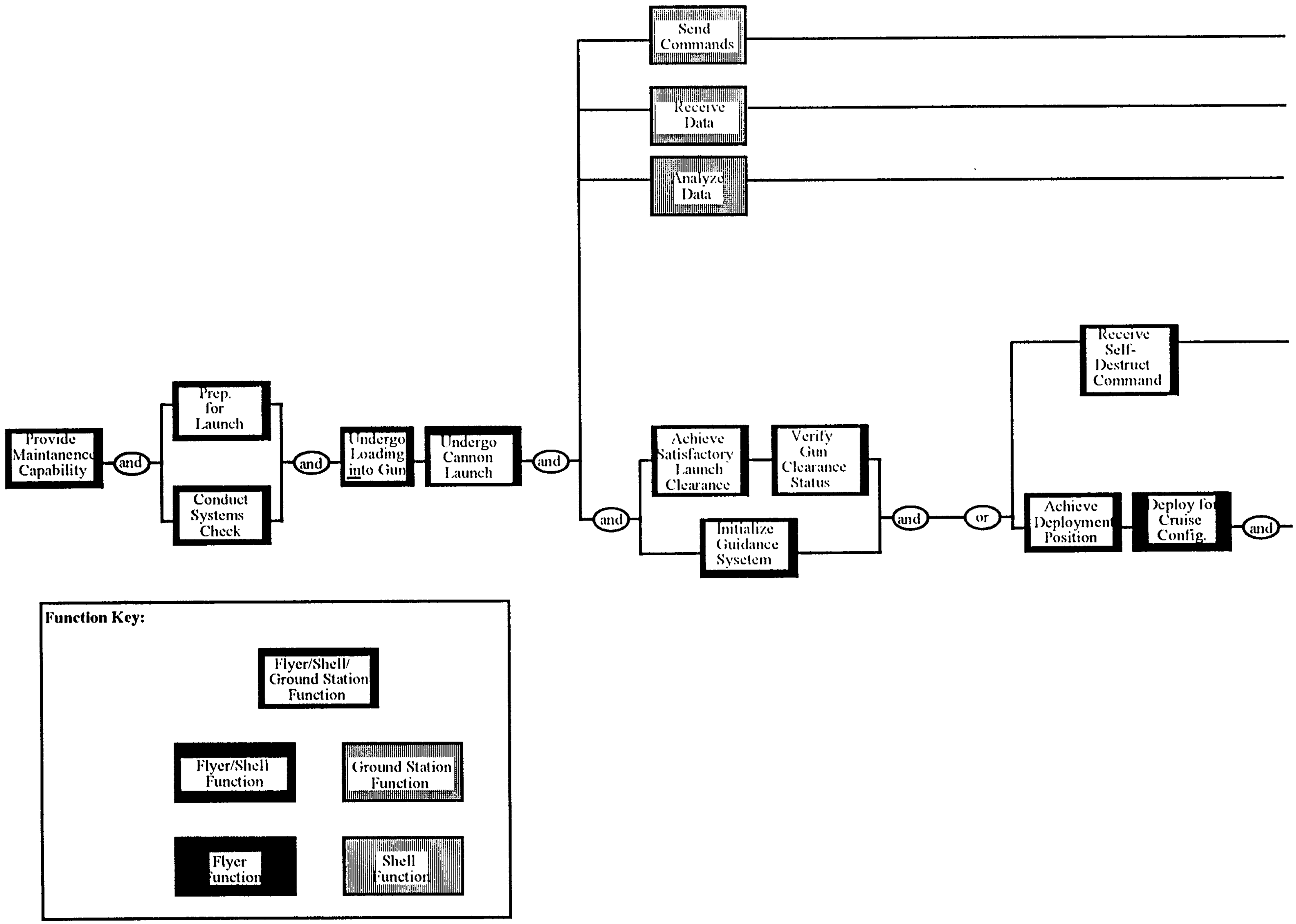
Earl Van Landingham
Office of Space Access & Technology, NASA

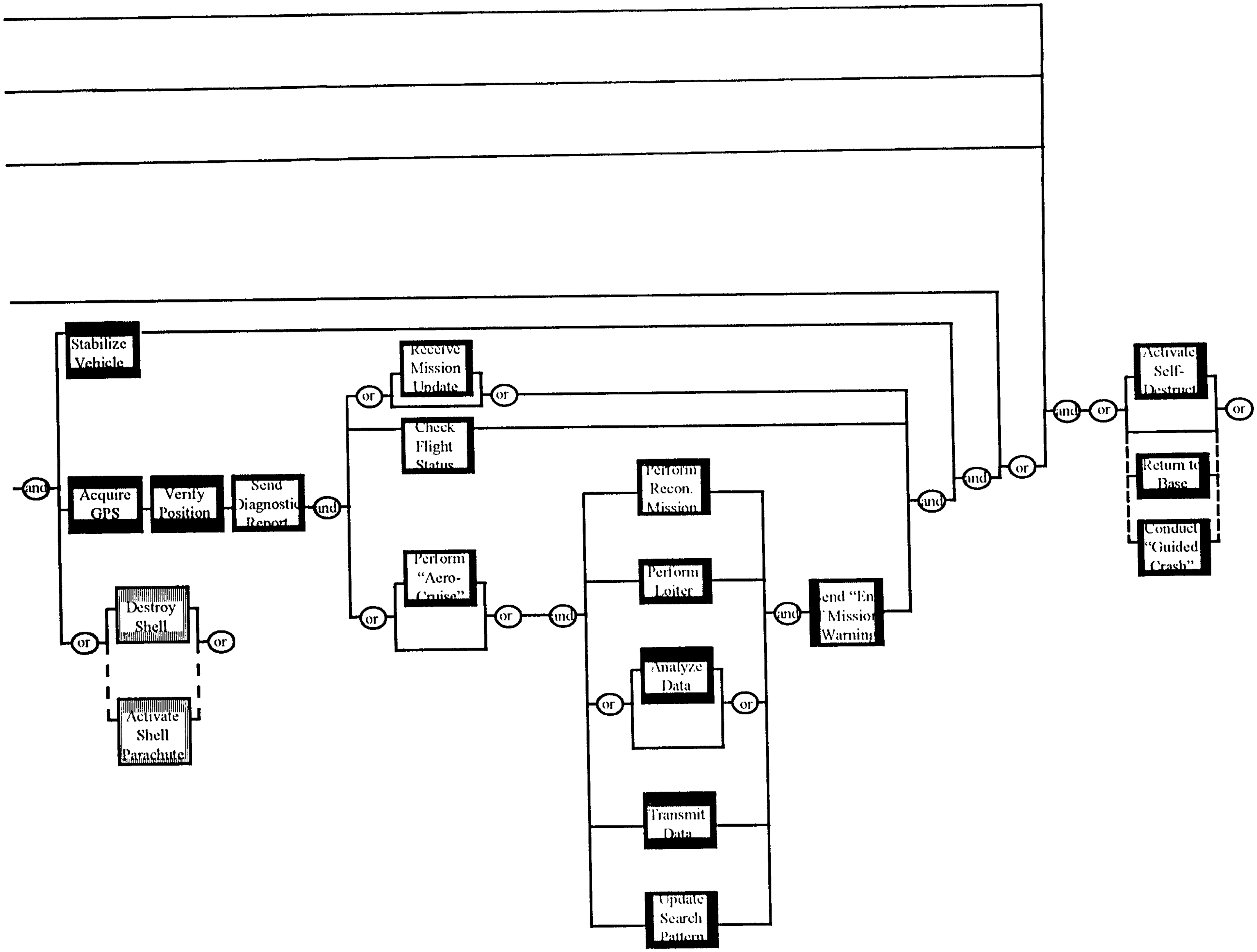
Gary A. Steinberg
Strategic Management - Office of Policy and Plans, NASA

Jay Henn - Director
Policy and Plans, NASA

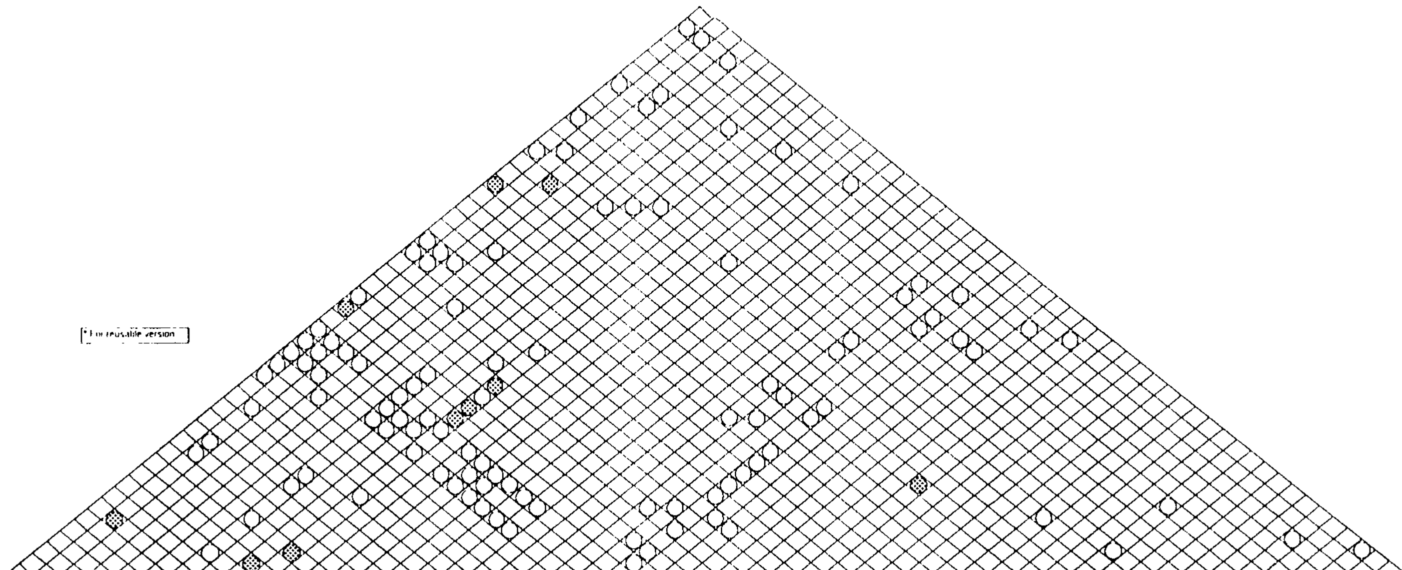
Peter J. Kennedy Jr. - Director - Emerging Markets
The Futures Group

Appendix B: Functional Flow Diagram for WASP


Provide Maintanence Capability
and
Prep. for Launch
Conduct Systems Check
and
Undergo Loading into Gun
Undergo Cannon Launch
and
Send Commands
Receive Data
Analyze Data
and
Achieve Satisfactory Launch Clearance
Verify Gun Clearance Status
Initialize Guidance Syscetem
and
or
Receive Self-Destruct Command
Achieve Deployment Position
Deploy for Cruise Config.
and
Function Key:
Flyer/Shell/ Ground Station Function
Flyer/Shell Function
Ground Station Function
Flyer Function
Shell Function


and
Stabilize Vehicle
Acquire GPS
Verify Position
Send Diagnostic Report
and
or
Destroy Shell
or
Activate Shell Parachute
or
Receive Mission Update
or
Check Flight Status
or
Perform "Aero-Cruise"
or
and
Perform Recon. Mission
Perform Loiter
or
Analyze Data
or
Transmit Data
Update Search Pattern
and
Send "End Mission" Warning
and
and
or
and
or
Activate Self-Destruct
or
Return to Base
Conduct "Guided Crash"

Appendix C: Quality Function Deployment for WASP



[* For reusable version]

Customer Needs \ Technological Requirements	Importance	Low inert mass fraction	Efficient aerodynamic design	Lightweight materials	High energy density	Flight path control	Efficient on-station propulsion	Minimize component size	Staging	Robust power system	Low subsys. power reqt	Minimal delivery basket	Flexible sensor system (zoom)	Flight system disturbance rejection	High sensor pointing acc	Target recognition capability	Accurate Navigation	High platform stability
Long range	5	9	9	9	3	9	9	3	3	1	1							
Long loiter	10	9	9	9	9		9	9	9	9	9	3					1	
Long operational time	10	3	3	9	9	3	3		3	9	9	9	3	3			1	
Maximum field of view	8					1	3						9					1
Maximum image resolution	8					1	3						9	9	9	9		3
Acc. image pos. determination	9					1							1	9	9	3	9	9
Minimum self-destruct debris	4							3	1									
Low cost	10	3							3									
Near real time info. processing	9									1				1				
High degree of autonomy	8	1			3	3	1			1				3		3	9	
Long shelf life	4									1								
Strong stealth chars	5			3				1			3							
Ease of operations	10			1		3							3	1			1	
Ease of maintainability	8										3							
High reliability	8									3				3				
High extensibility	5	3	3	3	1	3	3		3	3			3	3	3	3	3	3
Short launch time	3																	
Very safe	10																	1
Technical importance	7837	218	180	205	274	169	238	122	184	245	227	120	228	265	180	138	198	138
		8	6	10	8	6	8	4	8	9	8	4	8	10	6	5	7	5
Objective Target Values		0.2	23:1 glide slope	carbon-fiber	400 Whr/kg													

Customer Needs \ Technological Requirements	Easily destroyable parts	Self-destruct mech	High design commonality	COTS/standard components	Simple mfg & assem	Inexpensive components	High data throughput	Large bandwidth comm	Long range comm	On-board intelligence	Environmentally robust subsys	Minimize transmissions	Low visual signature	Low RADAR signature	Low acoustic signature	Low IR signature	Simple user interface
Long range									1								
Long loiter											1						
Long operational time											1	1	1	1	1	1	
Maximum field of view																	
Maximum image resolution							1	3									
Acc. image pos. determination							9	9		1							
Minimum self-destruct debris	9	9															
Low cost			9	9	9	9											3
Near real time info. processing							9	9	3	3							
High degree of autonomy							3	3	1	9		3					1
Long shelf life											9						
Strong stealth chars		1										9	9	9	9	9	
Ease of operations			1	3			3	3	3	3	1						9
Ease of maintainability			3	3	3					1							3
High reliability			3			1					3						
High extensibility		3	9	9			1	3	3	1			1	1	1	1	3
Short launch time				1	1					1							3
Very safe	3	1								3	3						
Technical importance	66	68	196	195	120	96	220	246	101	202	120	79	60	60	60	60	179
	2	2	7	7	4	3	8	9	3	7	4	2	2	2	2	2	6
Objective Target Values	cat food can	cat food can				total < $30,000			75-200 miles								

Customer Needs \ Technological Requirements	Similar handling chars. to peers	Maximize Automated Fxns	Minimize operator training	Robust shell	Effective diagnostics	Component accessibility	Minimal Mechanical Systems	Proper payload loading (g's)	Reliable components	High MTBF	High g components	Weather resistance	Sensor modularity	Adaptable on-board intel	Minimal system prep	Fail-Safe Design Concept	Mistake-Proof Mntnce. Cncpt
Long range												1					
Long loiter												3					
Long operational time									1			3		1			
Maximum field of view																	
Maximum image resolution																	
Acc. image pos. determination																	
Minimum self-destruct debris																	
Low cost		3	3		3	3	3								1		
Near real time info. processing														3			
High degree of autonomy		9	1		1				1					9			
Long shelf life	1			3		1	3		1	3		3					
Strong stealth chars																	
Ease of operations	9	9	9	9	3				3				3	3	3		
Ease of maintainability	3			9	9	9	9						3				
High reliability				3			9	9	9	9	9	9			1		
High extensibility						1		3				3	9	9			
Short launch time	3	3	1										3		9		
Very safe	3			3		1		1	3	3	3					9	9
Technical importance	160	201	131	237	149	130	195	97	154	114	102	164	111	164	75	90	90
	6	7	4	8	5	4	7	3	5	4	3	6	4	6	2	3	3
Objective Target Values	same shell sizes							>10,000 g's			>10,000 g's	water proof					

Appendix D: MathCAD Worksheet for Hybrid Rocket Preliminary Design

This worksheet uses the preliminary design process for a hybrid rocket that is laid out in pages 428-433 of Space Propulsion Analysis and Design (SPAD). The resulting hybrid rocket is sized to be placed inside of a 5 inch artillery shell for the WASP flier application. The engine is designed to use liquid oxygen for the oxidizer and HTPB for the solid propellant. Equations numbers given in parantheses are the numbers of the equations used from SPAD.

Requirements (chosen to meet the WASP mission requirements):

$$M_{imax} := 15 \cdot kg \qquad M_{pay} := 5 \cdot kg$$

$$FW_{min} := 0.3 \qquad \Delta V := 100 \frac{m}{sec}$$

Basic Decisions (based on SPAD):

$$N_{ports} := 8 \qquad OF_i := 1.2 \qquad P_{c.i} := 1.4 \cdot 10^6 \cdot Pa$$

Determine Engine Size and Feed System Pressure Levels:

Assuming an optimal O/F os 2.1, use Appendix B of SPAD for thermochemical parameters:

$$T_{c.opt} := 3593K \qquad \gamma_{opt} := 1.231$$

$$M_{opt} := \frac{22.84}{1000} \cdot \frac{kg}{mole} \qquad cstar_{opt} := 1747.4 \frac{m}{sec}$$

$$\lambda_{opt} := 0.98$$

Choose (based on Figure 7.25 and subtracting 10 seconds of Isp due to the fact that Figure 7.25 is calculated for space engines:

$$\varepsilon := 30 \qquad I_{sp} := 310 sec \qquad P_c := 7 \cdot 10^6 \cdot Pa$$

Calculate feed system pressure levels (5.16, 5.18, 5.20):

$$P_{di} := 0.2 \cdot P_c \qquad P_{di} = 1.4 \cdot 10^6 \cdot Pa \qquad P_{df} := 35000Pa$$

$$P_{oxd} := 57100Pa \qquad P_{oxtank} := P_c + P_{di} + P_{df} + P_{oxd} \qquad P_{oxtank} = 8.492 \cdot 10^6 \cdot Pa$$

$$P_{pressurant} := 40 \cdot 10^6 \cdot Pa$$

Use Goal Seek in Excel to solve for M_e (5.15):

$$M_e := 4.199265$$

Solve for P_e (5.14):

$$P_e := P_c \cdot \left(1 + \frac{\gamma_{opt} - 1}{2} \cdot M_e^2\right)^{\frac{\gamma_{opt}}{1-\gamma_{opt}}} \qquad P_e = 1.881 \cdot 10^4 \cdot \text{Pa}$$

Determine initial propellant flow requirements:

Initial thermochemical parameters (from p.430 of SPAD):

$$\gamma_i := 1.304 \qquad I_{spi} := 250\,\text{sec} \qquad cstar_i := 1545 \frac{\text{m}}{\text{sec}}$$

$$T_{ci} := 2203\text{K} \qquad M_i := \frac{17.2}{1000} \cdot \frac{\text{kg}}{\text{mole}}$$

Determine mass flow rates (5.29, 5.30):

$$mdot_{prop} := \frac{FW_{min} \cdot M_{imax}}{I_{spi}} \qquad mdot_{prop} = 0.018 \cdot \frac{\text{kg}}{\text{sec}}$$

$$mdot_{fuel} := \frac{mdot_{prop}}{1 + OF_i} \qquad mdot_{fuel} = 0.008 \cdot \frac{\text{kg}}{\text{sec}}$$

$$mdot_{ox} := OF_i \cdot mdot_{fuel} \qquad mdot_{ox} = 0.01 \cdot \frac{\text{kg}}{\text{sec}}$$

Size the system:

$$m_{final} := M_{imax} \cdot \exp\left[-\frac{\Delta V}{\left(I_{sp} - 10\,\text{sec}\right) \cdot 9.807 \frac{\text{m}}{\text{sec}^2}}\right] \qquad m_{final} = 14.499\text{kg}$$

$$m_{prop} := M_{imax} - m_{final} \qquad m_{prop} = 0.501\text{kg}$$

Make an assumption regarding the O/F shift:

$$OF_{average} := 2.3$$

$$m_{fuel} := \frac{m_{prop}}{1 + OF_{average}} \qquad m_{fuel} = 0.152\text{kg}$$

$$m_{ox} := m_{prop} - m_{fuel} \qquad m_{ox} = 0.349\text{kg}$$

$$m_{inert} := M_{imax} - M_{pay} - m_{prop} \qquad m_{inert} = 9.499\,kg$$

Configure combustion ports:

Set oxidizer mass flux and number of ports (based on typical numbers from SPAD):

$$N := 8 \qquad G_{oi} := 350 \frac{kg}{m^2 \cdot sec}$$

Calculate the port geometry (7.82, 7.83, and Figure 7.23):

$$mdot_{oxport} := \frac{mdot_{ox}}{N} \qquad mdot_{oxport} = 0.001 \cdot \frac{kg}{sec}$$

$$A_{iport} := \frac{mdot_{oxport}}{G_{oi}} \qquad A_{iport} = 3.506 \cdot 10^{-6} \cdot m^2$$

$$G_{fi} := \frac{G_{oi}}{OF_i} \qquad G_{fi} = 291.667 \cdot \frac{kg}{m^2 \cdot sec}$$

$$\theta_p := \frac{\pi}{N} \qquad \theta_p = 0.393 \cdot rad$$

$$h := \sqrt{\frac{A_{iport}}{\tan(\theta_p)}} \qquad h = 0.003\,m$$

$$b := 2 \cdot h \cdot \tan(\theta_p) \qquad b = 0.002\,m$$

$$P_{iport} := 2 \cdot \frac{h}{\cos(\theta_p)} + b \qquad P_{iport} = 0.009\,m$$

Choose regression rate parameters (from Table 7.5):

$$n_p := .618 \qquad m_p := .142 \qquad a_p := .00002$$

Calculate the port length (7.88):

$$mdot_{fuel} := mdot_{fuel} \cdot 1 \cdot \frac{sec}{kg} \qquad mdot_{fuel} = 0.008 \qquad G_{oi} := G_{oi} \cdot 1 \cdot \frac{m^2 \cdot sec}{kg} \qquad G_{oi} = 350$$

$$G_{fi} := G_{fi} \cdot 1 \cdot \frac{m^2 \cdot sec}{kg} \qquad G_{fi} = 291.667 \qquad P_{iport} := P_{iport} \cdot 1 \cdot \frac{1}{m} \qquad P_{iport} = 0.009$$

$$L_p := \left[\frac{mdot_{fuel}}{N \cdot 950 a_p \cdot \left(G_{oi} - G_{fi}\right)^{n_p} \cdot P_{iport}}\right]^{\frac{1}{1-m_p}}$$

$$L_p = 0.149$$

$$L_p := L_p \cdot m$$

Determine the radius of the grain (from Figure 7.23):

$$V_{fport} := \frac{m_{fuel}}{N \cdot 950 \frac{kg}{m^3}} \qquad V_{fport} = 1.999 \cdot 10^{-5} \cdot m^3$$

$$A_{fport} := \frac{V_{fport}}{L_p} - A_{iport} \qquad A_{fport} = 1.305 \cdot 10^{-4} \cdot m^2$$

Solve for the fuel web thickness using Excel's Goal Seek function (from Figure 7.23):

$$w := 0.005291m$$

$$r_{chole} := \frac{w}{\sin\left(\theta_p\right)} - w \qquad r_{chole} = 0.009 m$$

$$r_{grain} := h - 2 \cdot w - r_{chole} \qquad r_{grain} = 0.022 m$$

$$d_{grain} := 2 \cdot r_{grain} \qquad d_{grain} = 0.044 m$$

The system dimensions are then:

$$L_p = 5.87 \cdot in \qquad d_{grain} = 1.734 \cdot in$$

Size and configure components (3.133, 5.25, 7.103):

$$A_t := \frac{mdot_{prop} \cdot cstar_i}{P_c} \cdot 3 \qquad A_t = 0.119 \cdot cm^2$$

$$d_t := 2 \cdot \sqrt{\frac{A_t}{\pi}} \qquad d_t = 0.39 \cdot cm$$

$$A_e := \varepsilon \cdot A_t \qquad A_e = 3.576 \cdot cm^2$$

$$d_e := 2 \cdot \sqrt{\frac{A_e}{\pi}} \qquad d_e = 2.134 \cdot cm$$

Assuming a conical nozzle with a 15 degree half angle, the length is given by:

$$L_n := \frac{d_e - d_t}{2 \cdot \tan(15 \cdot deg)} \qquad L_n = 3.255 \cdot cm \qquad L_n = 1.281 \cdot in$$

Using a bell nozzle can increase can decrease the nozzle's length:

$$L_n := 0.675 L_n \qquad L_n = 0.865 \cdot in$$

$$V_n := \pi \cdot \left(\frac{d_e}{2}\right)^2 \cdot L_n \qquad V_n = 7.855 \cdot cm^3$$

The mass of the nozzle can then be determined:

$$m_{prop} := m_{prop} \cdot \frac{1}{kg}$$

$$m_n := 125 \cdot \left(\frac{m_{prop}}{5400}\right)^{\frac{2}{3}} \cdot \left(\frac{\varepsilon}{10}\right)^{\frac{1}{4}} \qquad m_n = 0.337 \qquad m_n := .33727 kg$$

Determine total combustion chamber length adding the grain radius to the overall length as an aft mixing section:

$$L_c := L_p + \frac{d_{grain}}{2} \qquad L_c = 6.737 \cdot in$$

$$V_c := \pi \cdot \left(\frac{d_{grain}}{2}\right)^2 \cdot L_c \qquad V_c = 260.84 \cdot cm^3$$

Estimate the thrust chamber mass using an aluminum case:

$$F_{tu} := 4.14 \cdot 10^8 \cdot Pa \qquad \rho := 2800 \frac{kg}{m^3}$$

$$P_{burst} := 1.5 P_c \qquad P_{burst} = 1.05 \cdot 10^7 \cdot Pa$$

Calculate the chamber wall thickness using a factor of safety of 1.25:

$$t_{cwall} := \frac{2 \cdot 1.25 P_{burst} \cdot \frac{d_{grain}}{2}}{F_{tu}} \qquad t_{cwall} = 0.14 \cdot cm$$

Determine the material volume required:

$$V_o := \left(\pi \cdot d_{grain} \cdot L_p\right) \cdot t_{cwall} \qquad V_o = 28.82 \cdot cm^3$$

$$m_{cwall} := \rho \cdot V_o \qquad m_{cwall} = 0.081 \cdot kg$$

Determine the injector mass (from Chapter 5):

$$m_{inj} := \rho \cdot \pi \cdot \left(\frac{d_{grain}}{2}\right)^2 \cdot .005\,m \qquad m_{inj} = 0.021 \cdot kg$$

Determine the total thrust chamber mass:

$$m_{tc} := m_n + m_{cwall} + m_{inj} \qquad m_{tc} = 0.439\,kg$$

Size the oxidizer tank using ~radius of the shell minus the wall thickness as the radius of the oxidizer tank:

$$P_{oxtank} = 8.492 \cdot 10^6 \cdot Pa \qquad \rho_{ox} = 1142 \frac{kg}{m^3}$$

$$V_{ox} := \frac{m_{ox}}{\rho_{ox}} \qquad V_{ox} = 305.93 \cdot cm^3$$

$$r_c := \frac{3.5}{2} \cdot in \qquad r_c = 4.445 \cdot cm$$

$$l_c := \frac{V_{ox}}{\pi \cdot r_c^2} \qquad l_c = 4.929 \cdot cm$$

$$l_c = 1.94 \cdot in$$

$$A_c := 2 \cdot \pi \cdot r_c \cdot l_c \qquad A_c = 137.651 \cdot cm^2$$

$$P_{burst} := 2 \cdot P_{oxtank} \qquad P_{burst} = 1.698 \cdot 10^7 \cdot Pa$$

$$t_{oxwall} := \frac{P_{burst} \cdot r_c}{F_{tu}} \qquad t_{oxwall} = 0.182 \cdot cm$$

$$m_{oxtank} := A_c \cdot t_{oxwall} \cdot \rho \qquad m_{oxtank} = 0.07 \cdot kg$$

Size the pressurant tank:

$$V_{press} := \frac{m_{ox}}{3 \cdot \rho_{ox}} \qquad V_{press} = 101.977 \cdot cm^3$$

$$r_p := \frac{3.5}{2} \cdot in \qquad r_p = 4.445 \cdot cm$$

$$l_p := \frac{V_{press}}{\pi \cdot r_p^{\,2}} \qquad l_p = 1.643 \cdot cm$$

$$l_p = 0.647 \cdot in$$

$$m_{ptank} := \frac{P_{pressurant} \cdot V_{press}}{9.807 \frac{m}{sec^2} \cdot 2500 m} \qquad m_{ptank} = 0.166 \, kg$$

$$m_{press} := V_{press} \cdot \rho_{ox} \qquad m_{press} = 0.116 \, kg$$

$$m_{support} := 0.1 \cdot \left(m_{tc} - m_{oxtank} - m_{ptank} \right) \qquad m_{support} = 0.068 \, kg$$

$$m_{prop} := m_{prop} \cdot kg$$

Determine the total rocket system mass by summing all of the individual component masses:

$$m_{Hybrid} := m_{prop} - m_{oxtank} - m_{tc} - m_{press} - m_{ptank} - m_{support}$$

$$m_{Hybrid} = 1.361 \, kg$$

Determine the total rocket system volume by summing all of the individula component volumes and adding in 20% for structural supports:

$$V_{Hybrid} := 1.2 \cdot \left(V_n - V_c + V_{ox} - V_{press} \right)$$

$$V_{Hybrid} = 811.921 \cdot cm^3$$

Determine the rocket engine's regression rate, which is the rate at which the webbing of the rocket burns:

$$L_p := \frac{L_p}{m}$$

$$\rho := 950 \qquad r_{chole} := \frac{r_{chole}}{m}$$

$$\mathrm{rdot} := \left(\frac{a_p}{1-m_p}\right)\cdot G_{oi}^{\,n_p}\cdot L_p^{\,m_p}\cdot\left[1+\frac{2\cdot n_p\cdot\left(\frac{a_p}{1-m_p}\right)\cdot\rho\cdot L_p^{\,1-m_p}}{2\cdot r_{chole}\cdot G_{oi}^{\,1-n_p}}\right]$$

$$\mathrm{rdot} = 5.065\cdot 10^{-4}$$

$$\mathrm{rdot} := \frac{\mathrm{rdot}}{1.6}\cdot\frac{m}{sec}$$

Determine the time of flight, which is simply the thickness of the engine webbing divided by the regression rate:

$$t_{flight} := \frac{w}{\mathrm{rdot}} \qquad t_{flight} = 16.715\,sec$$